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IMPACTS OF TILE DRAINAGE ON WATER QUALITY

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IMPACTS OF TILE DRAINAGE

ON WATER QUALITY

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Ms. Jennifer Ross, who co-ordinated the literature review and assisted in field studies.

ABSTRACT

Impairment of water quality as a result of agricultural activity is desired neither by the farming community nor by recreational users of receiving water bodies. Removal of valuable pesticides, fertilizers and topsoil by surface or subsurface drainage represents an economic loss to agriculture and a potential pollution hazard to receiving waters. In order to evaluate this potential impairment of water quality, there is a need for accurate prediction of chemical contaminant and sediment loadings for different environments, loading conditions, and agricultural management strategies.

The objectives of the research described in this report were to define the processes involved in movement of contaminants through the soil or over the surface and into tiles or ditches draining agricultural fields, incorporate an understanding of these processes into a physically-based model, collect field data for calibration and verification, use the model to evaluate the effects of tile drainage on water quality, and provide guidance on potential management strategies.

Algorithms to represent processes for chemical transport through the soil profile and into the tile drains were developed. These algorithms were incorporated into TILE which is a continuous, physically-based hydrologic simulation model for tile-drained agricultural fields and basins. To obtain data for model testing and calibration, a co-operative field program was entered into with Agriculture Canada to monitor tile water quantity and pesticide concentrations from a tile-drained corn field at the Animal Research Centre in Ottawa. In addition, field studies were undertaken to define the physical parameters required by the model -- saturated hydraulic conductivity, soil type and depth, drainable porosity, infiltration characteristics -- field slopes and tile installation details. Following collection and reduction of the data, TILE was calibrated to ensure it would accurately reproduce the hydrologic response of the tile drained field. Testing of the water quality algorithms for the pesticide employed (metolachlor) was undertaken. Finally, various scenarios involving the methods of application of pesticides and fertilizers and the timing of rainfall were evaluated to determine the potential effects on nutrient or pesticide loss from the fields through the tile drains or from surface runoff.

1.0 INTRODUCTION

1.1 Overview of Agricultural Drainage

Agricultural land drainage involves the enhancement of the natural drainage process to remove excess water from farmland, thus increasing its productivity. In Ontario, two levels of agricultural drainage works can be identified: (i) tile or ditch drains at the field level, and (ii) municipal drains.

Tile Drainage

Tile drainage consists of a network (usually systematically controlled) of clay tiles or, more commonly, perforated plastic pipe, installed at a uniform depth below the crop root zone. Excess water percolates downwards and moves under the influence of gravity to the drain, where it is removed from the field (Figure 1.1).

The drains effectively keep the ground water table below the root zone, allowing aeration of the root zone, and preventing stress to the crop. In addition, the tile drains lower the spring water table more rapidly than would natural interflow or evaporation - thus allowing the farmer access to his field for earlier harrowing and seeding.

Municipal Drains

Municipal drains are either new or improved channels which convey the excess water from the fields to receiving creeks or rivers (Figure 1.2).

In Ontario, improvements to the natural drainage processes began as early as the original clearing of the land for agriculture in the early 1800's. The intensity of drainage improvement increased extensively, however, during the 1960's and 1970's. This was primarily due to the installation of tile drainage, and to increased grants available under the Drainage Act and the Special Drainage Assistance Programme.

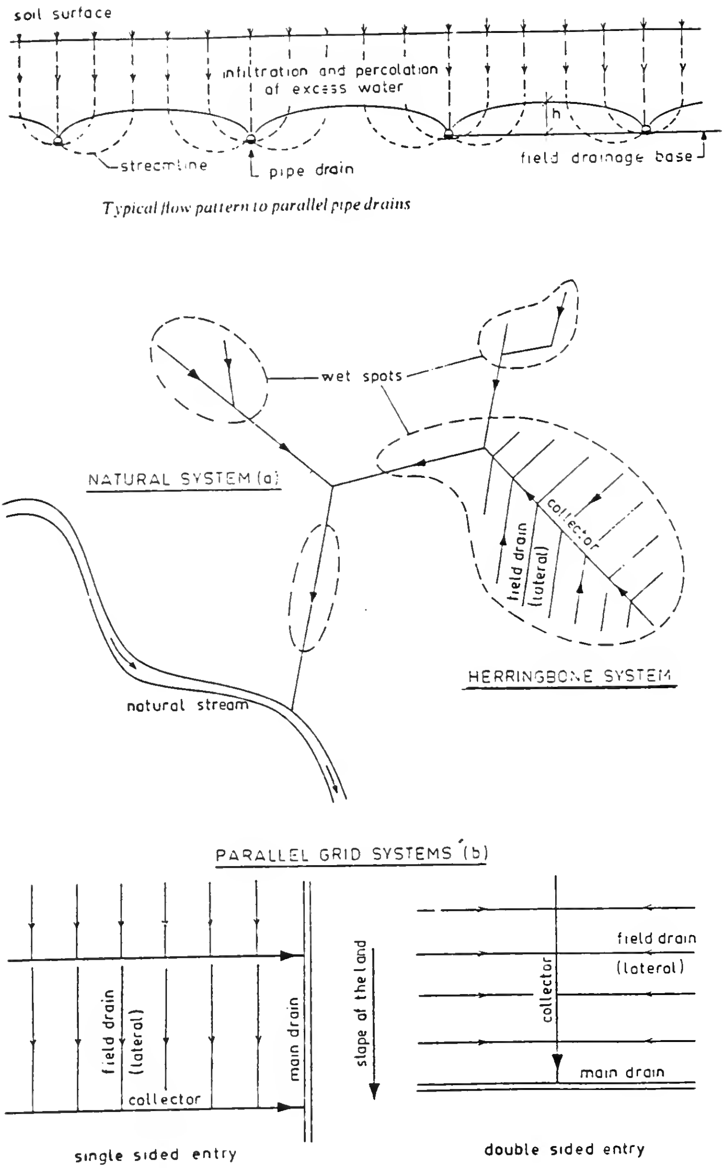
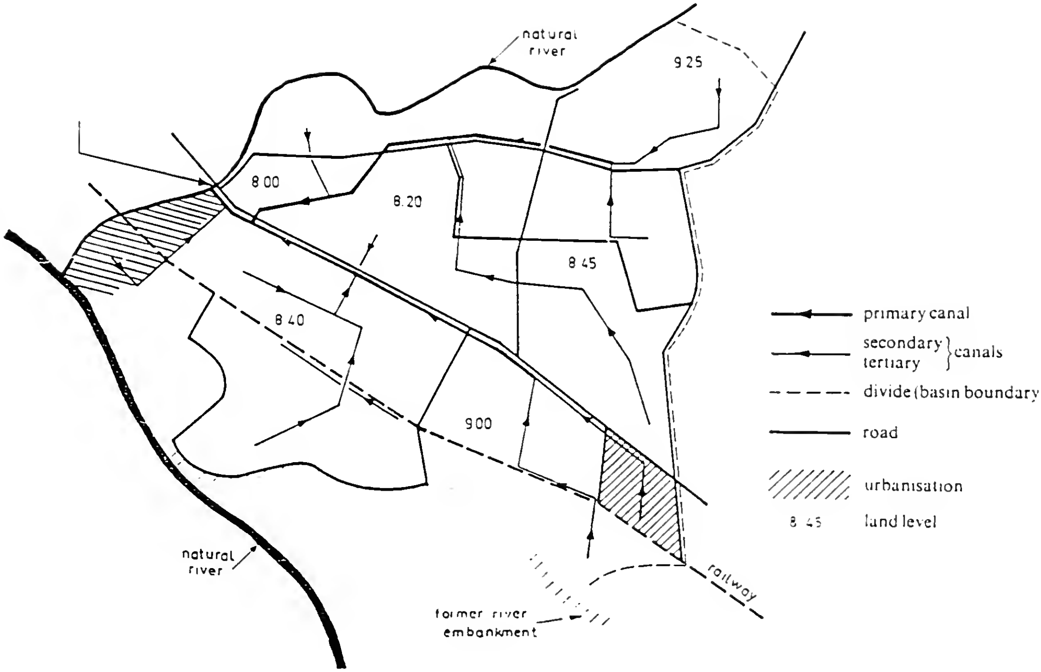


Figure 1.1 Illustration of tile drainage (Smedema and Rycroft 1983)



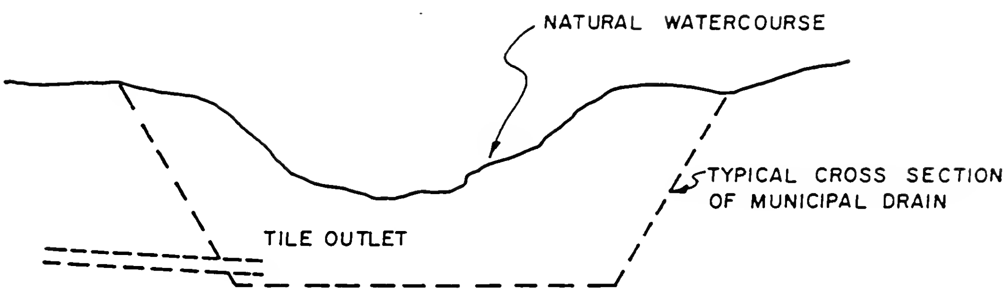


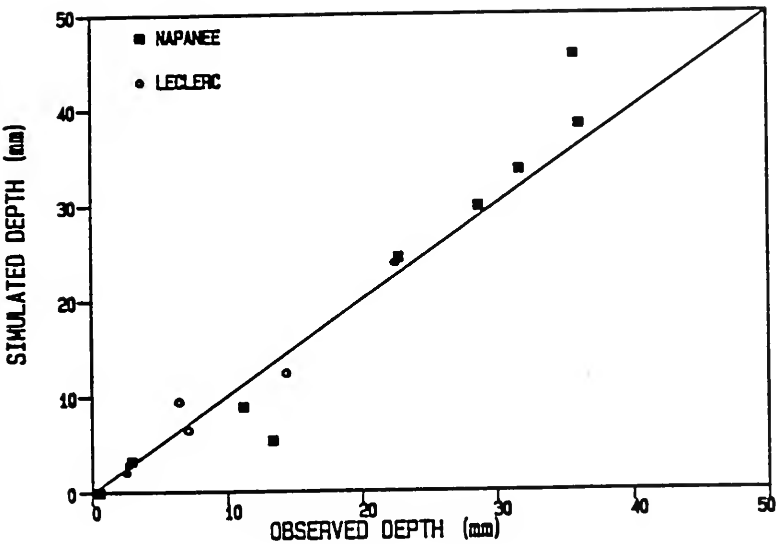
Figure 1.2 Illustration of municipal drains

1.2 Reference to Previous Queen's Project (No. 152 PL)

The research described in this report, which constitutes a natural extension of an earlier MOE funded project (No. 152 PL), addresses the impairment of water quality as a result of agricultural activity.

The objective of the earlier work (Paine and Watt 1988) was to investigate the hydrology of the agricultural drainage process, and its impacts on the land phase of the hydrologic cycle. Work included the development of an annotated bibliography following an extensive literature review. Statistical tests were performed on flow data in an attempt to identify trends in the data which could be attributed to the drainage process. Finally, the impacts of both tile drainage at the field level and ditch drainage at the small basin level were considered and analysed through the use of a physically-based hydrologic model capable of simulating the drainage process continuously through the frost free period. Required input includes field and tile geometry (field length and slope, number and spacing of drain tiles, depth of tile), soil characteristics (depression storage capacity, depth of ploughed layer and depth to impervious layer), groundwater parameters (saturated hydraulic conductivity and drainable porosity), and meteorological data (hourly rainfall and mean daily temperature). Output includes soil moisture storage, groundwater table height, subsurface flow and contribution to surface runoff.

The model was tested on two fields in southeastern Ontario. It successfully replicates observed flows and water tables for two distinct soils and for a wide range of antecedent conditions and storm rainfall. Figure 1.3 illustrates the success of simulation of event volumes of tile discharge and peak tile flows. Simulated and observed tile flow for a selected event are displayed on Figure 1.4.



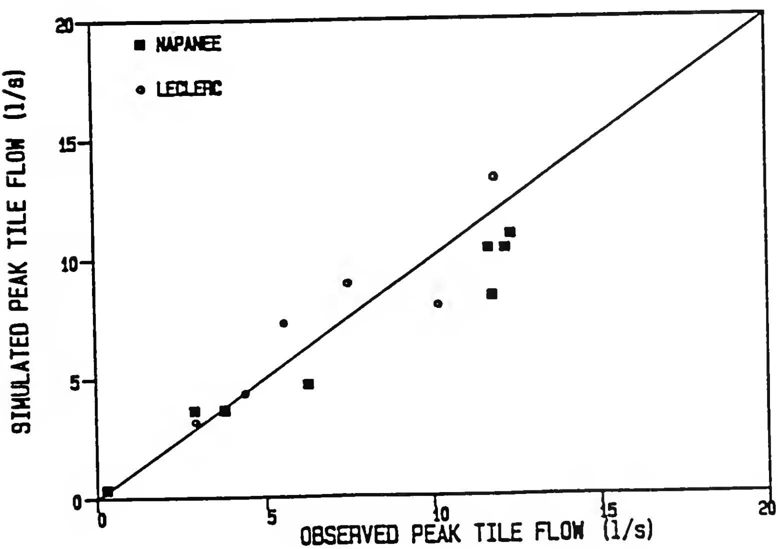


Figure 1.3 Observed and simulated depths and peak flows

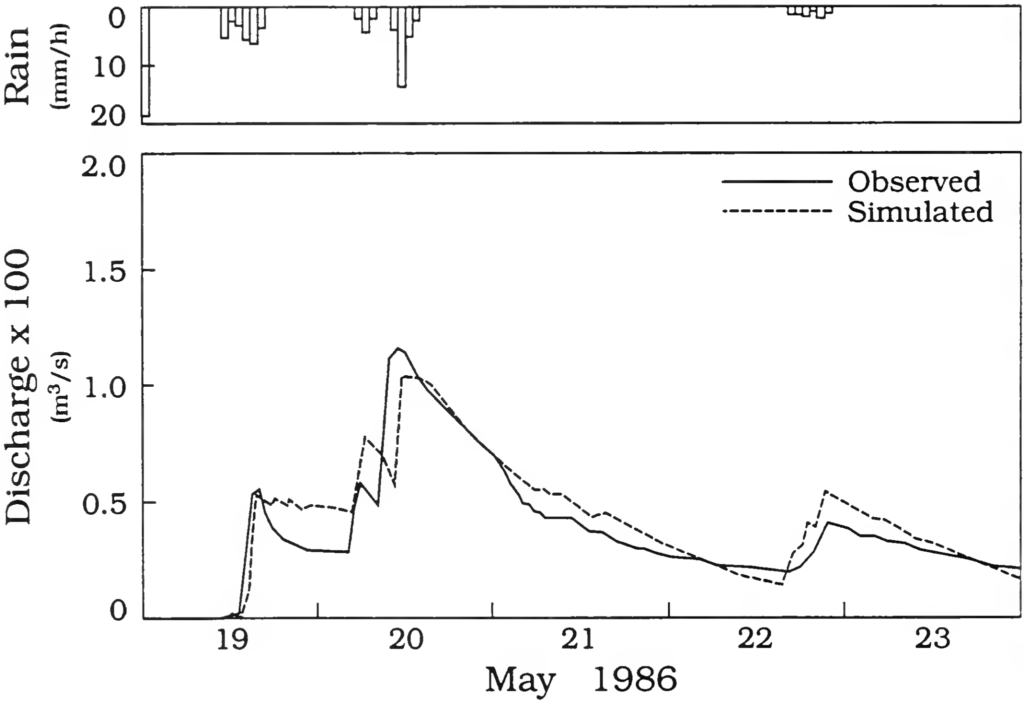


Figure 1.4 Observed and simulated hydrographs - Napanee Field

The model, in its continuous mode, was used to assess the impacts of tile drainage systems on peak and low flows at the field level and at the small basin level. The application of the model to the test fields led to the following conclusions regarding the impacts of agricultural drainage in Ontario.

- The hydrologic response of a tile drained field is particularly sensitive to antecedent moisture conditions prior to rainfall events. It is impossible to comment on the impacts of tile drainage through an examination of independent rainfall events. It is necessary to consider seasonal periods to establish the changes in the frequency of various surface or subsurface hydrograph peaks and volumes.

- A simple deterministic hydrologic model can, when calibrated, be used successfully to assess the impacts of tile drainage on peak and low flows for various field characteristics and soil types.

- Tile drainage in southeastern Ontario does affect peak and low flows. Drainage exacerbates low flow periods during summer months (July and August) and reduces the frequency of high flows as a result of intense rainfall events.

- Tile drainage does not significantly change the total volume of runoff, but the relative magnitudes of surface and subsurface runoff are significantly changed. The subsurface flow, which would be interflow in the untiled case and largely tile flow in the tiled field, is increased significantly for tiled fields. Because of this alteration in flow paths to receiving streams, it is expected that other processes requiring water as a transport medium will be altered significantly. These processes could include soil erosion, nutrient runoff, and herbicide and insecticide transport and decay mechanisms.

The report included the recommendation that

- the use of the model be extended to other areas of Ontario for testing;
- the model and other information be disseminated to other government agencies as it becomes available with a view to ultimately applying the information in a practical manner

for land use assessment or tile drainage design; and

- the model be linked to water quality algorithms to assess the impacts of drainage activity on water quality in receiving streams.

1.3 Study Background and Terms of Reference

1.3.1 Need for Research

As identified in the proposal for the study, the impairment of water quality as a result of agricultural activity is desired neither by the farming community nor by recreational users of receiving water bodies. Removal of valuable pesticides, fertilizers and topsoil by surface or subsurface drainage represents an economic loss to agriculture and a potential pollution hazard to receiving waters. In order to evaluate this potential impairment of water quality, there is a need for accurate prediction of chemical contaminant and sediment loadings for different environments, loading conditions and agricultural management strategies.

This prediction requires knowledge of not only contaminant behaviour but knowledge of the tile drainage hydrological regime. Under previous work, an assessment of the impacts of tile drainage systems on peak and low flows at the field and small basin levels resulted in the conclusion that tile drainage did not significantly alter the total runoff volume but did change the relative magnitudes of surface and subsurface flows. Because of this alteration in flow paths to receiving streams, processes related to the presence of water, such as soil erosion, nutrient transport and herbicide and insecticide transport and decay mechanisms, might also be significantly changed.

A comprehensive evaluation of water quality impacts is best accomplished by a combination of selective measurement and more general modelling. The model employed should be deterministic and capable of simulating both water quantity and quality at the field level. A few quantity models that meet these criteria are available. However, because of the lack of applicable quality models, a major task in this project is the development of physically-based quality algorithms that can be linked to hydrologic quantity models to accurately predict chemical contaminant and sediment loadings.

The section which follows outlines the terms of reference for the study as originally proposed to the Ontario Ministry of the Environment.

1.3.2 Objectives of the Work

The objectives of the work as set out in the proposal were:

1. to define the processes involved in movement of contaminants through the soil or over the surface and into the tiles or ditches draining agricultural fields,
2. to incorporate an understanding of these processes into a physically-based model capable of simulating water quality changes on a basin scale,
3. to collect field data for calibration and verification of the model,
4. to use the model to evaluate the effects of tile drainage on sediment and water quality loadings, and
5. to provide guidance on the use of the model for evaluation of potential management strategies.

1.3.3 Methodology

The methodology, as set out in the proposal, was as follows:

Year 1

- A comprehensive literature survey will be conducted to define the state-of-the-art regarding the effects of both tile drainage and open ditch drainage on soil erosion and water quality of receiving waters.
- A field program will be implemented to establish an inventory of existing land use, crop type, tillage practices, sources of contaminants, etc. over the test basin.
- Field studies will be conducted to establish a surface water budget during low flow periods. Stream gauging and current meter traverses will be carried out throughout the test basin.
- Laboratory studies will be conducted to test, develop and calibrate devices for measuring surface water quantity and quality.
- Field and laboratory studies will be conducted to determine natural background levels of

major, minor and trace chemical constituents in shallow groundwaters in order to establish control levels for tests on agricultural fields.

Year 2

- Field studies will continue in order to collect a larger data base on which to assess the need for model revisions and calibrations as necessary. If necessary, field programs will be modified based on the conclusions drawn from the Year 2 studies.
- Data will be collected during the winter of Year 2 to allow determination of the effects of the spring melt period on the transport mechanisms of salts (fertilizers), pesticides and suspended solids.
- With the development of the calibrated model, trial remedial measures will be synthesized to enable the researchers to comment on the potential effectiveness of management schemes.
- the agricultural quality/quantity model will be documented and merged with a user-friendly interface to allow its use by other researchers.
- The final report will be prepared and submitted.

Year 3

- The field measuring equipment will be installed on various land use units e.g. surface runoff from hayfields, row crops, pasture and tile runoff from lands under row crops, and in fallow. Additional quality/quantity measurements will be taken at various points on the receiving stream itself.
- Algorithms for water quality transport models for various chemical constituents under tile drainage, surface runoff etc. will be developed and tested as sampling data becomes available. Source areas of chemical constituents and sediment yields will be identified and constituent budgets determined.

During year 2 of the research, changes to the methodology were made to accommodate a research agreement made with Agriculture Canada. The change involved the field specific monitoring program which was altered to involve fields at the Agriculture Canada Research Station at the Ottawa Experimental Farm. Reasons for this were as follows.

1. A good data base on metolachlor, crop type, tile layout and water quantity presently existed at this site; these would permit a confident calibration of the TILE model.

2. A co-operative arrangement had been made with Dr. N. Patni (Research Scientist on Agricultural Waste) to ensure a level of field data collection, and chemical analysis which would be difficult to achieve elsewhere.
3. The tile drained field we had been monitoring at Napanee, Ontario was no longer in corn and consequently pesticides were no longer being applied. (We continued to monitor the field for water quantity data from the tiles.)

2.0 LITERATURE REVIEW

2.1 Preamble

Agricultural water quality modelling undertaken to date has focussed primarily on heterogeneous drainage basins. Many models (CPS, CREAMS 2) use simplified relationships such as the Universal Soil Loss Equations to establish sediment or nutrient losses. These models, often applied uncalibrated and unverified, are useful for providing an approximate index for evaluating nutrient or sediment loss potential between watersheds. However, an accurate assessment or understanding of the interaction of more minute processes cannot be gleaned from this approach.

The more complex models (e.g. HSPF, SWAM) subdivide the watersheds being modelled into homogeneous units to apply transport and decay processes for sediment and chemical movement. Several of these models possess a structure or modelling methodology which may be adapted to modelling at the field level.

The objectives of this literature review were to:

i) identify recent (since 1980) papers defining the state-of-the-art in water quality modelling for small agricultural watersheds,

ii) define the focus of research in Canada, and

iii) identify processes, models and field data which could assist in the development and calibration of a physically-based model for simulation of water quantity and quality interactions at the field level.

The TILE model for water quantity modelling at the field level involves the use of three water storage reservoirs: surface storage, upper soil water storage, and lower soil water storage. Transport mechanisms between and out of these storage elements include surface runoff, evaporation, infiltration, percolation, groundwater recharge and tile flow. The challenge is to incorporate water quality processes within a parallel framework to model contaminant storage, transfer and decay. As a prelude to the design and testing of water quality transport algorithms,

a literature review was conducted to determine the state-of-the-art.

2.2 Methodology and Sources

Several methods of obtaining information were used. Although the modelling project is a long term one and a literature review is basically open- ended, the aim was to find as much up to date information as possible in a fairly short period of time. Listed below are the various methods used along with their relative success.

Computer Databases

The use of computer databases was found to be efficient method of finding applicable references with an economy of effort. Information available from the databases was often limited to the title, author and keywords, however, making additional screening somewhat more time consuming. Database searching was carried out by inputting selected keywords concerning water quality, agricultural drainage and pesticides. Listed below are the various databases consulted along with and evaluation of their applicability to the literature review.

ELIAS: This is an Environment Canada database. It did not turn up anything with less than 189 references or more than zero for the keywords selected.

AQUAREF: This database was more useful; ten references were identified, of which three were relevant.

GEOREF: This database provided 27 relevant references although some difficulty was experienced in locating copies of the papers.

AGRICOLA: Nineteen references were identified through this database.

CANOLE: This database seemed to be less relevant to this study since it was related more to the food aspects of agriculture. However, it turned up 22 potentially useful references.

Engineering Index

There was a wealth of information available through the Engineering Index; this included a detailed abstract on each reference or paper. Unfortunately, the index was difficult to use and involved a considerable amount of time. Limited cross referencing was available resulting in the necessity for screening several references in order to find applicable papers.

Journals

Since the Engineering Index does not contain the more recent articles (less than 1 - 2 years old), the latest issues of applicable journals were scanned to find articles that had not yet been published in the Index. Several articles were located in this manner.

Conference Proceedings

Occasionally, conference proceedings may be of use, and often correspondence can be set up with those registered at a conference. One such useful conference was the Conference on Environmental Aspects of Irrigation and Drainage conducted by the A.S.C.E. in 1976. Information was obtained through an article in the proceedings as well as through correspondence with those involved.

Queen's Computer Library System

The lack of cross referencing in the Queen's Library System made general searching very tedious. However, with a specific reference, title or name or when investigating a secondary reference the computer system was a useful tool.

Interviews

Personal interviews were conducted with Dr. N.K. Patni, Chairman of the Animal Waste Utilization Program at the Agriculture Canada Animal Research Centre in Ottawa and Dr. J.D.

Gaynor, an Environmental Chemist with the Agriculture Canada Research Station at Harrow, Ontario. Both of these researchers provided relevant papers which were included in this report.

2.3 Results

As a result of searching through the various sources listed above, over 60 potentially relevant publications were identified. These publications were divided into seven categories: general models, field studies, soil loss, pesticide studies and measurements, pesticide processes and models, nutrient studies and measurements, and nutrient processes and models. In the following sections, the published works are summarized in the form of tables listing all references along with brief summaries of the more pertinent items.

2.3.1 General Models

The General Models category contains models which are quite sophisticated. Such models tend to deal with complete systems and may include both pesticide and nutrient components. Several such models are listed in Table 2.1 below. As yet, no models have been developed specifically for watersheds with tile drained fields.

Table 2.1 References for general models

Reference		Jurisdiction	Comments
Author	Date		
Ward et al.	1988	Ohio	ADAPT pesticide transport model
Leonard et al.	1987	Georgia	GLEAMS groundwater loading model
Alonso, DeCoursey	1985	Colorado	Small watershed model
Burn, McBean	1985	Waterloo	Optimization of water quality modelling
Krider	1985	Washington	SCS response to CREAMS 2
Lance	1985	Oklahoma	Wetlands model considerations
Leonard, Ferreira	1985	Georgia	CREAMS2- nutrient & pesticide components
Pionke et al.	1985	Pennsylvania	Small watershed model
Rudra et al.	1985	Guelph	CREAMS application in S. Ontario
Smith, Knisel	1985	Georgia	CREAMS2 methodology
Chapman	1982	Australia	Transport of non-conservative chemicals
Jennings et al.	1982	Indiana	Multicomponent equilibrium chemistry
Lorber, Mulkey	1982	United States	CREAMS, ARM, CPS comparison

There are many processes which are commonly employed in pesticide models, as outlined by Chapman (1982). These processes can be divided into physical, chemical, and biological categories. Physical processes include advection, three-dimensional dispersion, sedimentation and resuspension of particulates and atmospheric reaeration. Chemical processes include simple ionic reactions, hydrolysis, oxidation-reduction reactions, precipitation and adsorption. Biological processes include direct uptake by aquatic vegetation from the water column or sediment, and photosynthesis and respiration of the biomass. All of these processes are affected by environmental conditions such as rainfall, wind, insolation and temperature.

The art of successfully representing such a complex system is to model only those processes which significantly affect the variables of interest, for example, water table elevation and tile flow in the quantity case and contaminant concentration of surface flow and tile flow in the quality case.

Variables of secondary interest include, in the quantity case, soil water contact, and in the quality case, contaminant concentrations within the soil column.

There is an abundance of literature on the more popular models, such as CREAMS or CREAMS2 (Chemicals, Runoff, and Erosion from Agricultural Management Systems), ARM (Agricultural Runoff Management), CPS (Continuous Pesticide Simulation) and SWAM (Small Watershed Model)

CREAMS2 is the most popular model being applied in Ontario. The components of both CREAMS and CREAMS2 can be found in Smith and Knisel (1983) and in Leonard and Ferreira (1983). CREAMS contains several submodels, including hydrology, erosion-sedimentation, nutrient cycling, pesticide, plant growth and meteorology. CREAMS was tested in southern Ontario by Rudra et al. (1985) on corn plots with several years of verification. During testing, the hydrology submodel was modified for use in southern Ontario, in order to take into account seasonal variations in soil erodibility and hydraulic conductivity brought on by changes in temperature. These modifications apparently greatly improved the accuracy of the model for fate application in Ontario. Leonard et al. (1987) reported the development of GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) which incorporates a component for vertical flux of pesticides into the management-oriented, physically-based CREAMS model. Ward et al. (1988) described the combination of components of GLEAMS and DRAINMOD, a popular drainage management model, to predict pesticide concentrations in subsurface drainage as well as in runoff.

Lorber and Mulkey (1982) compared CREAMS to two other models, ARM and CPS. The differences between these models, most of which are in the hydrology and erosion components, are reviewed in the paper. All three models require a substantial amount of

calibration, necessitating field data and knowledge of sensitivity of the model to input parameters for reliable use. CPS, which uses SCS and USLE equations, was found to be the easiest to use due to the amount of background literature available. CREAMS was more complex, with more input parameters, but had good user documentation. All three models produced results which correlated closely with observed data.

Another popular model for pesticide and nutrient transport is SWAM. The chemical component of this model includes a routing model and phosphorus, nitrogen and pesticide algorithms. These algorithms are outlined in Alonso and DeCoursey (1983) and in Pionke et al. (1983), along with necessary input parameters, output data and assumptions involved in model use.

The models described above provide a useful framework for creation of a water quality model for use with fields or small watersheds in eastern Ontario. The references consulted assist in the understanding of the necessary process components of a pesticide model. Users manuals for the above models describe the algorithms adopted for modelling purposes in more detail.

With respect to the research goal of development of a water quality model for tile drained agricultural fields and small watersheds, this survey of available models lacks specific information concerning flow through tile drains. There seems to be very little information available on the quality of tile drained waters.

2.3.2 Field Studies

The Field Studies category contains several broad spectrum field studies dealing with a variety of water quality concerns as well as two studies of bacterial contamination which were not strictly nutrient or pesticide studies.

Documented Canadian field study programs geared towards the observation or analysis of agricultural activities and their relationship to water quality are notably few (Table 2.2). Among the first field study programs for monitoring of processes on agricultural watersheds were

those established by the Pollution from Land Use Activities Reference Group (PLUARG). This group came about as a result of the 1972 USA--Canada Great Lakes Water Quality Agreement and the focus on agricultural watersheds was based on an interest in developing an index to determine the soil's potential to transfer pollutants to surface and groundwater. A paper by Coote et al. (1982) describes the selection and preliminary monitoring of 11 agricultural sites for a two year period. Correlation coefficient matrices for various water quality parameters versus watershed characteristics were developed to ascertain key components in the water quality processes. Percent clay content in the agricultural soil was found to be highly correlated with the watershed's potential for transferring pollutants. A related study (PLUARG 1978), coordinated by Dr. N.K. Patni, investigated pollutant transport to subsurface tile drainage water from application of animal manure. A potential for groundwater pollution by residual soil nitrogen was discovered and as well, the presence of atrazine and its degradation products was detected.

Table 2.2 References for field studies

Reference		Jurisdiction	Comments
Author	Date		
Howard, Falck	1986	Ontario	Land use, groundwater
Patni et al.	1985	E. Ontario	Bacterial concentration
Coote et al.	1982	Great Lakes	PLUARG studies
M.O.E.	1981	E. Ontario	Hydrology report on Wilton Cr.
M.O.E.	1979	E. Ontario	IHD report on Wilton Cr.
Patni, Hore	1978	E. Ontario	Pollution from farm operation

Wilton Creek near Napanee, Ontario was studied fairly extensively during the International Hydrologic Decade and was the subject of two reports by the Ontario Ministry of

the Environment (1979, 1981). These studies dealt primarily with the analysis of water budgets and the chemistry of groundwater.

Other field studies of particular relevance to this research project are those undertaken by Agriculture Canada. Patni et. al., at the Ottawa Experimental Farm, have concentrated on monitoring BOD, nutrients and pesticides in the tile discharge from row cropped fields (primarily corn). Although results and observations, particularly with respect to BOD, nutrients and bacterial concentrations, have been published much of the data collected since 1974 has not yet been analyzed. Recent work undertaken at the Agriculture Canada Research Station at Harrow, Ontario has concentrated on the fate of pesticides in surface and tile water. At present research is continuing on the quantification of herbicide losses (atrazine and metolachlor) from four test plots on a poorly drained clay loam soil. Each of the four test plots is subjected to a different tillage system (John D. Gaynor, personal communication).

2.3.3 Soil Loss

The Soil Loss category includes four papers dealing with soil loss and erosion processes and one field measurement study of streamflow sediment. The four references are summarized in Table 2.3. Foster et al. (1983) suggested several criteria for and features of a hydrologically based replacement for the Universal Soil Loss Equation (USLE) which provides better estimates of soil loss from individual storms. The EPIC (Erosion - Productivity Impact Calculator) model, described by Williams (1983), includes components for modelling both wind and water erosion using respectively the Onstad and Foster modification to the USLE and the Cole modification of the Manhattan, KS, wind erosion equation. Wall et al. (1982) analyzed suspended sediment yields from small southern Ontario agricultural watersheds. They considered both sheet/rill erosion and bank erosion processes by application of the USLE and mapping of streambanks.

Table 2.3 References for soil loss

Reference		Jurisdiction	Comments
Author	Date		
Wilson, Barfield	1986	Kentucky	specific soil detachment algorithm
Foster et al.	1985	Indiana	replacement for universal soil loss equation
Williams	1985	Texas	EPIC-erosion-productivity impact
Wall et al.	1982	Great Lakes	PLUARG research-suspended sediment & erosion processes
Ongley et al.	1981	E. Ontario	Characteristics of suspended solids

To complete a review of the state-of-the-art in soil loss analysis, information concerning modelling of other specific erosion processes and any available improvements to the USLE should be collected.

2.3.4 Pesticide Measurement Studies

The Pesticide Measurement Studies category includes a large number of papers detailing the results of measurements of pesticide persistence in soils and pesticide concentration in surface runoff and tile effluent. These references are listed in Table 2.4.

Smith (1982) reviewed existing field persistence studies and discussed the fates of a variety of herbicides in Canadian agricultural soils and the effects of those herbicides on soil fertility. Weber et al. (1980) tabulated physical characteristics of various types of pesticides and summarized the results of studies on the measurement of losses to runoff.

The herbicides most commonly used in eastern Ontario are atrazine and cyanazine which

control broadleaf and some grassy weeds in corn and sorghum. Most authors (Wu et al. 1982, Spencer 1983, Ghadiri et al. 1984) agree that herbicide movement in runoff water occurs primarily in present dissolved aqueous form and is not highly correlated to the sediment present. Atrazine concentration in field runoff water was shown to be related to the number of days after field application by a log relationship (Wu et al. 1982). Atrazine concentration declines naturally in the soil through microbial detoxification, plant absorption and metabolism, and chemical catalysis and detoxification. Losses of atrazine to external drainage are relatively low, typically on the order of two percent of that applied (Frank et al. 1982) for Southern Ontario. Wauchope (1978) showed that the runoff available pesticide half life for atrazine is seven to ten days, which limits major losses to a two-week critical period following herbicide application.

Through the use of a "tilted bed" simulator, Wauchope (1987) compared different formulations of atrazine and their runoff correlations. He confirmed earlier studies showing no discernible relationship between sediment load and atrazine load and no indication of enrichment. In a three-year Pennsylvania study, Hall et al. (1984) investigated the transport of cyanazine (another triazine herbicide) under no-till live mulch corn planting and conventional tillage practices. Because the live mulch reduced surface runoff by up to 97 percent over conventional tilling, cyanazine losses were reduced by up to 99 percent. Percolation of atrazine into the soil column for untiled fields was not found to be particularly significant with little or no detection below depths of 70 cm (Ghadiri et al. 1984). Krawchuk et al. (1987) detected residues of chlorothalonil in the tile drain outfall for Manitoba test fields. Also, Muir and Baker (1978) detected residues of triazine herbicides in tile drainage water (1.2-1.6 m depth) indicating vertical movement through the soil column for a loamy sand in Quebec. Similar work in British Columbia (Hogue et al. 1981) suggested a greater subsurface mobility for herbicides in sandy loam soil versus loam or clay loam soils.

Metolachlor is an herbicide also used to control similar weeds in similar crops to the triazine herbicides. Patni et al. (1987) compared soil persistence and tile effluent concentrations for metolachlor, atrazine and cyanazine. Buttle (1990) and Buttle and Harris (1989) reported the results of a study of transport of metolachlor in dissolved and suspended sediment phases in runoff water.

Table 2.? References for pesticide measurement studies

Reference		Jurisdiction	Comments
Author	Date		
Best et al.	1990	Saskatchewan	Pesticides, nutrients
Buttle	1990	Peterborough	Metolachlor
Buttle, Harris	1989	Peterborough	Metolachlor
Patni et al.	1987	Ottawa	Atrazine, cyanazine
Krawchuk, Webster	1987	Manitoba	Pesticides
Wauchope	1987	Georgia	Atrazine, erosion
Ou et al.	1986	Florida	Aldicarb degradation
Bouchard, Lavy	1985	Arkansas	Hexizinone
Grover et al.	1985	Saskatchewan	2,4-D iso-octyl ester
Jaffe et al.	1985	Tennessee	Pesticides
Onishi et al.	1985	Washington	Chemical migration
Spencer	1985	California	Pesticides
Ghadiri et al.	1984	Nebraska	Atrazine, crop type
Glotfelty et al.	1984	Maryland	Atrazine, simazine
Hall et al.	1984	Pennsylvania	Cyanazine, crop type
Mayeux et al.	1984	Texas	Picloram dissipation
Hall et al.	1983	Pennsylvania	Atrazine, crop patterns
Nicholaichuk, Grover	1983	Saskatchewan	2,4-D spring runoff
Nkedi-Kizza et al.	1983	Florida	Diuron, 2,4,5-T
Wu et al.	1983	Maryland	Herbicides
Frank, et al.	1982	Guelph	Pesticide use
Smith	1982	W. Canada	Herbicides
Hogue et al.	1981	British Columbia	Herbicides, soils
Weber et al.	1980	United States	Pesticides
Miles, Harris	1978	London	Insecticide residues
Muir, Baker	1978	Quebec	Triazines, tiles
Wauchope	1978	Mississippi	Pesticides, surface water
Miles	1976	London	Insecticide residues
Sharom et al.	1973	London	Insecticide residues
Miles, Harris	1971	London	Insecticide residues

2.3.5 Pesticide Processes and Models

The Pesticide Processes and Models category includes papers which, rather than outlining the results of measurement studies, attempt to translate those results into the understanding of pesticide transportation and transformation processes necessary for model development (see Table 2.5).

Table 2.5 References for pesticide processes and models

Reference		Jurisdiction	Comments
Author	Date		
Olsen, Davis	1990	United States	Organic chemicals in groundwater
Dyer, Wilkie	1988	Canada	Vertical transport of inert Chemicals
Pierce, Wong	1988	Canada	Pesticide transport
McKay	1987	Canada	Environmental modelling
Corwin	1986	California	Chemical diffusion
Heathman et al.	1986	Oklahoma	Herbicides
Wagenet, Hutson	1986	New York	Nonvolatile pesticides
Green	1985	Hawaii	Pesticide sorption
Nash, Isensee	1985	Maryland	Pond pesticide processes
Wehtjee et al.	1984	Nebraska	Atrazine leaching
Willis, McDowell	1982	United States	Pesticides in runoff
Sharom et al.	1981	London	Pesticide movement and biodegradability
Miles et al.	1976	London	Insecticides, nutrients

Recent research on pesticide movement has focused primarily on studies involving

observations and measurements. While many of these observations are conclusive, it appears that little attempt has been made to formulate them into models describing pesticide movement and fates.

Green (1985) pointed out the necessity for simplifying the physical, chemical and biological pesticide fate processes included in modelling. He suggested that available independently measured input parameters will not support more detailed models. As a result, he applied linear approximations to the estimation of adsorption, desorption and solution concentration relationships.

Green then discussed the effects of assuming linearity in the modelled relationships and suggested methods of estimating sorption coefficients. He also identified soil organic carbon content and particle surface area as playing dominant roles in pesticide-soil interactions. Olsen and Davis (1990) provided a more detailed treatment of non-linear estimations of rate constants for processes affecting organic chemicals in groundwater systems. Pierce and Wong (1988), McKay (1987) and Willis and McDowell (1982) discussed the interactions of chemical processes with climatic factors in aquatic systems.

Nash and Isensee (1985) presented a thorough summary of pond pesticide processes including both partitioning and loss pathways. They estimated process rates using pseudo-first order reaction kinetics.

Other approaches, such as those developed by Heathman et al. (1986), Corwin (1986), and Wagenet and Hutson (1986) simulate pesticide movement with finite difference models. Wagenet and Hutson considered movement of aldicarb to demonstrate that their model could provide reliable and useful estimates of the mass flux of water and non-volatile pesticides in unsaturated soil.

Application of a linear model relating soil water content to solute retention was used by Wehtje et al. (1984) to assess herbicide movement through the soil column.

2.3.6 Nutrient Measurement Studies

This section contains references concerning specific nutrient measurement studies (Table 2.6). Neilsen et al. (1982) and Miller et al. (1982) measured nitrogen and phosphorus surface water loadings for southern Ontario watersheds. Phillips et al. (1982) investigated the influence of agricultural management practices on inorganic nitrogen and phosphate concentrations in subsurface tile discharge. Coote and Hore (1979) investigated groundwater contamination by nitrates and phosphorus from a feed lot. Miller (1979) compared contamination in mineral and organic soils. Gaynor (1979) measured phosphorous and biological indicator organisms to quantify domestic and agricultural pollution inputs. Finally, Bolton et al. (1970) compared plant nutrient losses in tile effluent for different cropping systems.

Table 2.6 References for nutrient measurement studies

Reference		Jurisdiction	Comments
Author	Date		
Miller et al.	1982	Great Lakes	Phosphorus loadings - PLUARG
Neilsen et al.	1982	Great Lakes	Nitrogen loadings - PLUARG
Mills, Zwarich	1982	Manitoba	Movement & loss of nitrate from sewage sludge placed on agricultural fields
Phillips et al.	1982	E. Ontario	Inorganic nitrogen and phosphate
Coote, Hore	1979	Guelph	Groundwater contamination by nitrates
Gaynor	1979	S. Ontario	Agricultural phosphorous
Miller	1979	Guelph	Nitrogen, phosphorus in mineral & organic soil
Webber	1978	Guelph	Nitrogen from sewage sludge
Coote, Hore	1976	Ottawa	Runoff & water quality from feedlots
Bolton et al.	1970	S. Ontario	Tile nutrient losses

These references fall into two general categories: measurements of contamination from agricultural activities and from disposal of sewage wastes on agricultural fields. The first of these categories is more important to the objectives of this study. More papers from different types of agricultural fields and different locations might be useful for development of a data base for comparison with later studies.

2.3.7 Nutrient Processes and Models

Several excellent references discussing nutrient processes and models were reviewed and are summarized in Table 2.7. Jones et al. (1985) described the EPIC model's method of producing reasonable long term predictions of total nitrogen and organic phosphorous topsoil pool sizes. Schnabel (1985) explained partitioning of ammonium between soluble and adsorbed phases of mixed suspensions and suggested a method for determining isotherm parameters from common soil properties. Williams and Lewis (1985) presented an in-stream water quality model for simulation of the dissolved oxygen profile in shallow streams which assumes that nitrification and denitrification processes occur simultaneously. Caskey and Schepers (1985) presented a comprehensive review of the effects of physical factors on environmental microbial activity. Sharpley et al. (1985) provided a useful generalized kinetic model describing the desorption of soil phosphorus.

Kunishi and Pionke have developed a model to describe liquid and solid phosphorus transport in streams that is related to the SWAM model but that may not be universally accepted. Wendt (1983) analyzed the physical factors affecting equilibrium phosphate concentrations (EPC's) that have been widely used to predict the pollution potential of soils and sediments. Finally, Cho et al. (1979) formulated a relationship between soil temperature, seasonal time and depth which allows calculation of soil denitrification intensities and capacities.

These references provide a fairly comprehensive review of nutrient processes as they include discussion of both instream and field level processes. Further information, especially in the form of usable behaviour models, at both levels, would be useful.

2.4. Summary

In summary, sound and comprehensive information was found to exist for field level processes involved in the degradation and transformation of pesticides. In addition, field studies undertaken by Agriculture Canada at Harrow and Ottawa, Ontario have yielded valuable water quantity and quality data for pesticide treated fields.

Table 2.7 References for nutrient processes and models

Reference		Jurisdiction	Comments
Author	Date		
Gillham	1988	S. Ontario	Nitrate behaviour in groundwater systems
Williams, Lewis	1986	N. Carolina	Simultaneous benthic nitrification-denitr.
Caskey, Schepers	1985	United States	Modelling microbial activity
Jones et al.	1985	United States Great Plains	Organic Nitrogen and phosphorous pools
Kunishi, Pionke	1985	Maryland	Model for solid & liquid P-transport in streams
Schnabel	1985	Pennsylvania	Ammonium partitioning
Sharpley et al.	1985	Oklahoma	Desorption kinetics in phosphorous transport
Wendt	1985	United States	Factors affecting phosphate concentration
Khyder, Cho	1983	Manitoba	Nitrification-denitr. of N-fertilizers in a controlled soil column
Ahuja et al.	1982	Oklahoma	Effects of soil type & rainfall on P-runoff
Cho	1982	Manitoba	Oxygen consumption & denitrif. kinetics
Cho, Mills	1979	Manitoba	Nitrification process kinetics
Cho et al.	1979	Manitoba	Denitrification intensity & capacity

Not all pesticides have had the same research treatment; atrazene has been used for some time in Ontario and has received the focus of much of the attention for field studies. Metolachlor, a relatively new compound, is being tested by Agriculture Canada but it is questionable if sufficient data exist to define confidently its transport and decay behaviour in a soil column.

For many models, efforts have been directed towards the basin scale where the field level processes are treated in an oversimplified fashion. Although the basic background information exists, convenient algorithms to link the field level processes and permit the determination of water quantity and quality budgets within the soil layers do not exist.

This literature survey confirmed the potential research value of a field level model to link hydrologic processes to pesticide chemical algorithms to further the understanding of pesticide transfer in an agricultural environment.

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3.0 CHARACTERIZATION OF STUDY AREAS

3.1 Wilton Creek Drainage Basin

3.1.1 Physical Characteristics and Land Use

Material which follows has been taken in part from Ostry and Singer (1981).

Location

The Wilton Creek basin is located on the north shore of Lake Ontario, 22 km west of Kingston. This study area is bounded on the south by Lake Ontario between longitudes 76° 38'W. and 76° 55'W., a distance of approximately 15 km and extends inland (northwest) from the Lake for a distance of approximately 15 km. Wilton Creek enters the study area from the northeast and flows southwestward across the study area to drain into Hay Bay at latitude 44° 11' N. and longitude 76° 56'W.

Physiography

The Wilton Creek basin is entirely within the Napanee plain. According to Chapman and Putnam (1966), the Napanee Plain is a flat to undulating plain of limestone which was scoured, scraped and stripped of any existing overburden by the glaciers during Pleistocene time. The soil is generally shallow over much of the physiographic region. The low areas are often found to be covered with a shallow veneer of stratified clay (Chapman and Putnam 1966).

The regional topographic gradient is in the order of 3 m/km towards Lake Ontario. Maximum relief is approximately 105 m. The Wilton Creek basin is long and narrow with a total length of 38 km and an average width of 3.5 km.

Land Use

Wilton Creek is predominantly an agricultural basin, and is largely cleared over the watershed. The basin to the north of Highway 401 (Figure 3.1) has approximately 60 percent of the land area in hay crops with 25 percent pasture and the remainder in mixed crops or corn. To the south of Highway 401 the agricultural use of the basin changes distinctly. Over 70 percent of the land area is in corn or soybean production with approximately 15 percent in hay or mixed crops. Less than 15% of the production area is devoted to pasture or is idle. Over 30

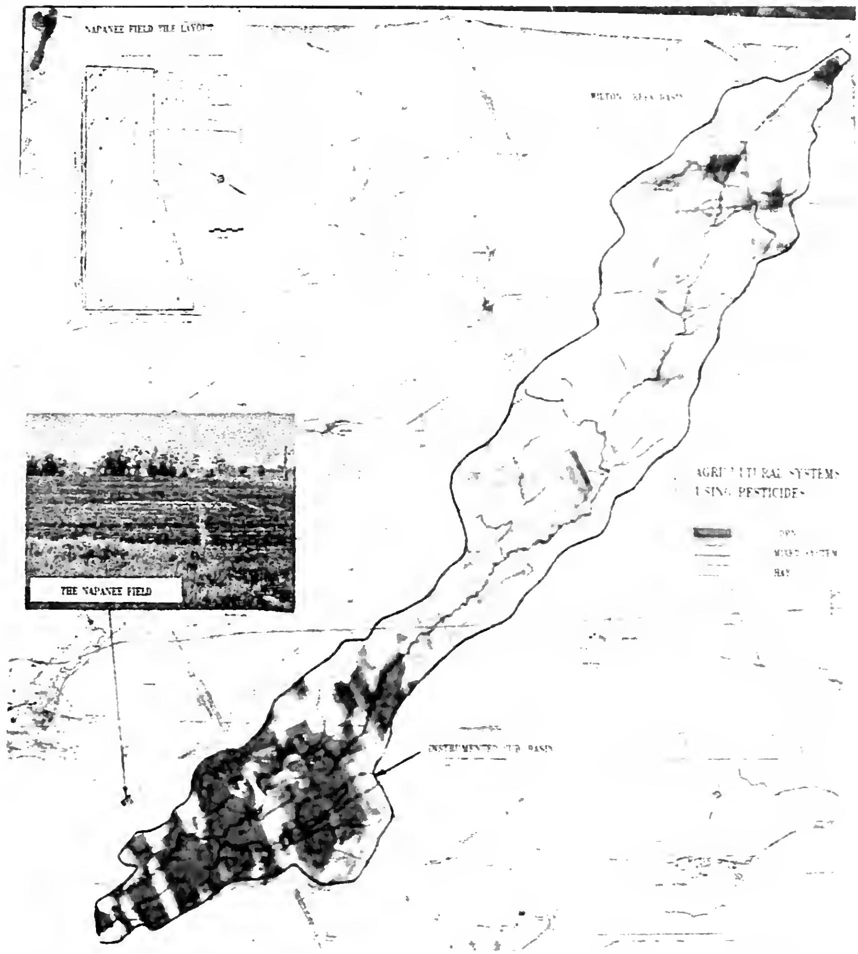


Figure 3.1 Land use - Wilton Creek basin

percent of the land under corn cropping is tile drained. This amount of tile drainage is relatively high for this area of southern Ontario.

3.1.2 Hydrology

Wilton Creek has had a Water Survey of Canada gauge located at Highway 2 near Morven since 1966 (O2HM004). The drainage area to the gauge is 112 km^2. The basin was the focus of studies during both the International Hydrological Decade and the PLUARG studies of the 1970's. Unlike the adjacent watersheds of the Napanee River and Millhaven Creek with headwaters in the Precambrian shield, Wilton Creek lies entirely within the limestone plain. As such the watershed possesses virtually no storage in the form of lakes or significant wetlands. Mean monthly flows at the gauge vary from a high of 4.2 m^3/s in March to a low of 0.14 m^3/s in August. Mean daily flows over the period of record range from a maximum of 44.3 m^3/s on March 22, 1980 to a low of 0 m^3/s on August 18, 1988 (Environment Canada 1989). The annual hydrograph (Figure 3.2) has an important impact on water quality loadings and concentrations. In the spring of the year when flows are higher, although contaminant loadings maybe high, concentrations will be low. These lower concentrations may not prove detrimental to aquatic life or water users of Wilton Creek but the high loadings may have a significant impact on receiving waters such as the Bay of Quinte. During the summer when flows are naturally very low, even small contaminant loadings of sediment or nutrients may be sufficient to elevate contaminant concentrations to dangerous or lethal levels for fish or other aquatic life.

With reference to Figure 3.2 it is noted that with no operable storage future flows can be expected to lie generally within the shaded range shown. Therefore, if either loadings or instream concentrations are to be reduced in the future it is clear that inputs must be reduced. If loadings to receiving waters are the primary concern then attention should be directed towards reducing the largest inputs whenever they may occur (Figure 3.2c). Conversely, if instream concentration are the primary interest then attention should be given to reducing inputs during periods of low flow (Figure 3.2d).

Regardless of the area of interest (loading or concentration) the difficulty lies in the

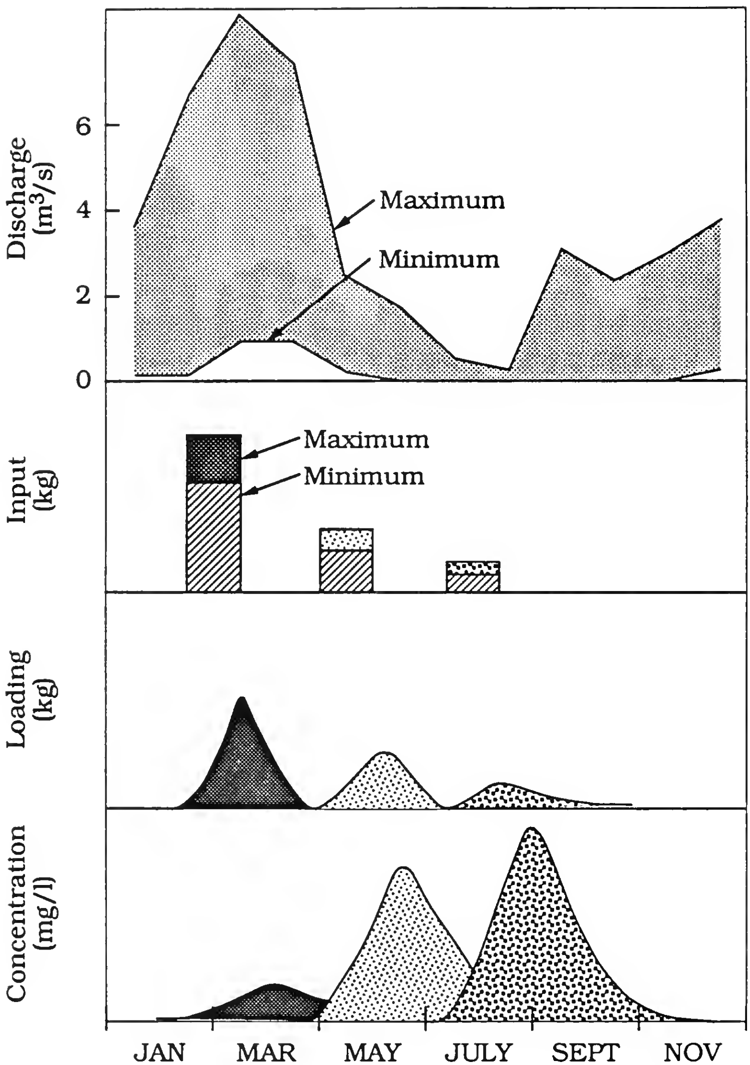


Figure 3.2 Annual hydrograph, contaminant input and instream concentration

identification of the differences and reasons for the differences between the contaminant mass applied and the contaminant mass which eventually appears in the receiving stream. This mass which is lost at the field level is a result of degradation, adsorption, or incorporation into the soil of the contaminant. Additionally, the mechanism by which this loss occurs is dependent on agricultural practise, soil type, drainage efficiency and on the rainfall volumes and timing which occur during the time potential contaminant is on the surface of a field. These complex physical and chemical interrelationships require the examination of the processes at the field level to gain an understanding of the manner in which pesticides, fertilizers etc. are transported through or over the soil surface to the receiving stream.

3.1.3 Erosion Potential

The potential for erosion or sediment loss from the Wilton Creek basin has been assessed in comparison with the erosion potential for other surrounding river basins. The watershed grouping used to delimit the boundaries of the Cataraqui Region Conservation Authority (CRCA) has been used assess the relative ranking of the Wilton Creek basin. This watershed grouping encompasses all watersheds draining to Lake Ontario and the St. Lawrence River from Napanee to Brockville.

The CRCA undertook a regional erosion assessment (CRCA 1985,1986) in an attempt to rank problem areas within their jurisdiction and to identify areas appropriate for educational or technical assistance. The assessment was undertaken in three phases. Phase I utilized the Universal Soil Loss Equation (USLE) to estimate potential gross soil erosion. Phase II used a sediment delivery ratio model to ascertain the potential for eroded sediment to be delivered to receiving streams. Finally, Phase III involved overlaying the results from the two previous model applications to identify and rank likely problem areas within the total watershed area.

Phase I

Soil erosion occurs in three basic forms. These include upland erosion caused by water, upland erosion caused by winds, and streambank and shoreline erosion. PLUARG investigations (PLUARG 1978) reveal that more than 65 percent of pollution entering Lake Ontario/St.

Lawrence River can be traced to upland soil erosion induced by water. As sediment is a major carrier of pollutants such as phosphorus, heavy metals, pesticides and other organic compounds, and as farmland occupies over 60 percent of area throughout the Authority watershed, the Universal Soil Loss Equation was used to assess erosion from agricultural areas.

The Universal Soil Loss Equation (Wischmeier and Smith 1978) calculates the average soil loss from sheet and rill erosion in tons/acre/year or in tonnes/hectare/year (tons/acre/year x 2.242). Sheet erosion occurs when rain washes a thin layer of soil from a field; rill erosion occurs when the soil is carried away in small water-etched channels. These are the two main modes of soil loss in rural southern Ontario. The USLE is as follows:

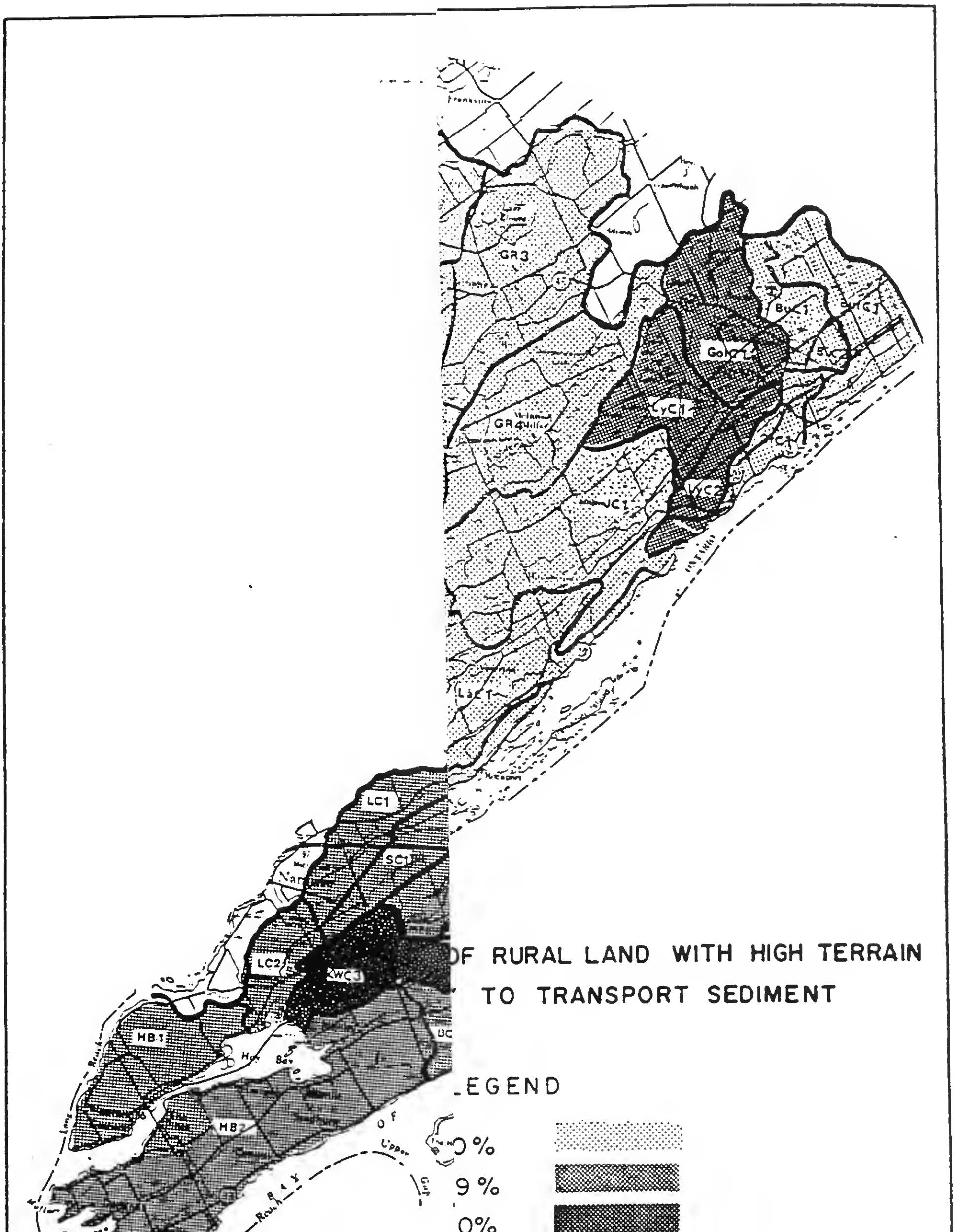
$$A = R \times K \times LS \times C \times P$$

where A is the average loss due to sheet and rill erosion in tons per acre per year
R is the rainfall factor
K is the soil erodability factor
LS is the length-slope factor
C is the vegetation factor
P is the management practices factor

A description of the factors and the detailed determination of values used may be found in CRCA (1985). Parameters for the USLE were determined on a sub-watershed basis to yield a ranking for the component basins in the CRCA watershed area. Figure 3.3 displays the results of Phase I in terms of potential erosion.

Phase II

Phase I of the Regional Erosion Assessment dealt with the determination of Potential Gross Erosion, through the application of the Universal Soil Loss Equation. However, not all of the eroded soil reaches a stream or receiving water body. Some of the material will be arrested by thick vegetation or buffer zones prior to entering a creek or stream. The proportion of available eroded soil which does reach a receiving water body is referred to as the 'delivery ratio'.



.tial erosion - Wilton Creek basin

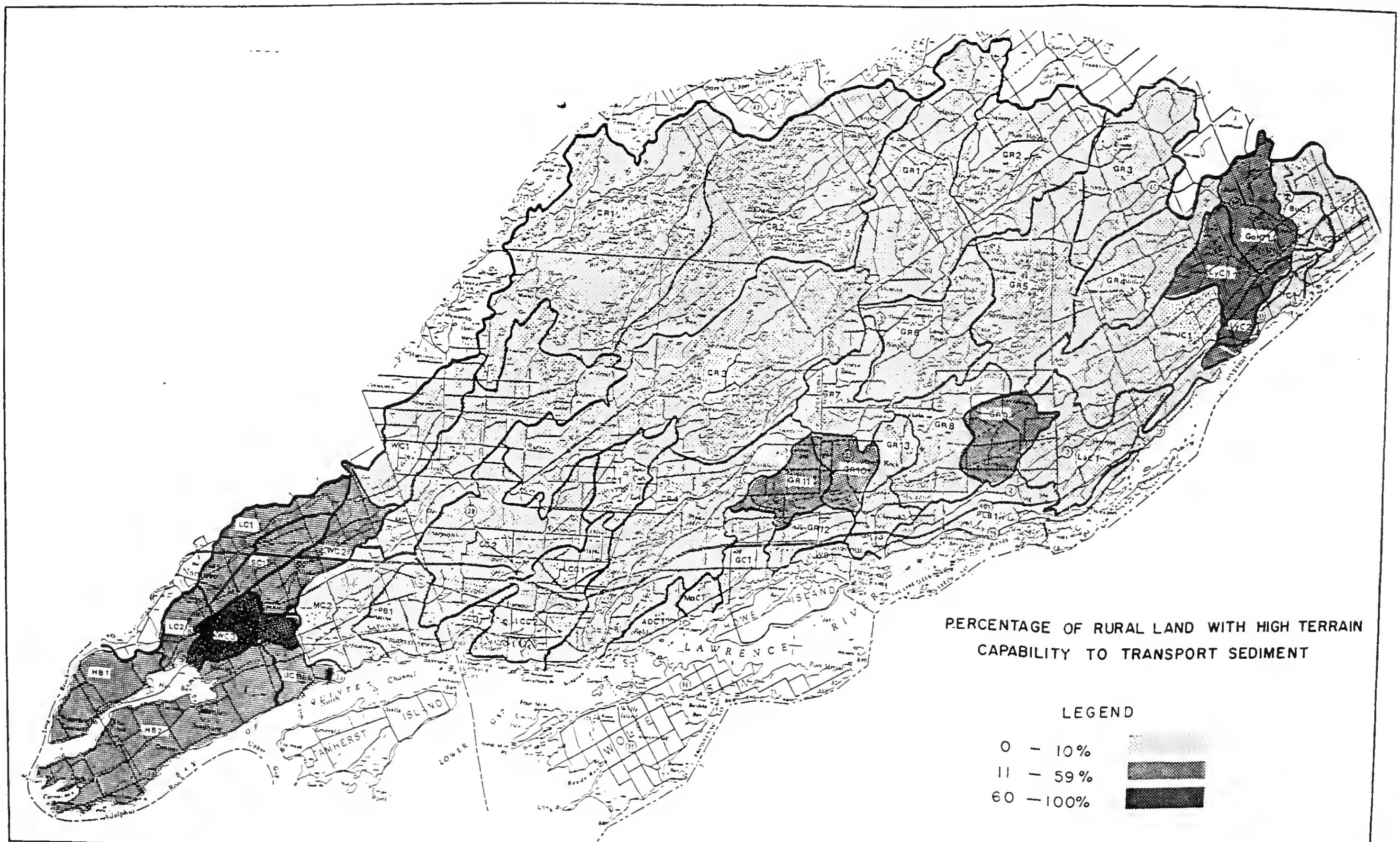


Figure 3.3 Potential erosion - Wilton Creek basin

A simplified methodology described in Environment Canada (1984) study was developed to permit the qualitative determination of the delivery ratio with the time and budget available. The method involves an overlay technique using agricultural capability and land use maps but limits the area of interest to the 0.25 kilometre strip of land on both sides of a stream or water body. The methodology involves the classification of sub-basins by land use, crop types, soil types and slopes. Details may be found in CRCA (1985). Figure 3.3 depicts the sub-basins which have a high terrain capability to transport sediment.

Phase III

Following the previous two exercises, the potential gross erosion can be 'multiplied' qualitatively with the delivery ratio to evaluate the quantities of sediment reaching the receiving water bodies. It is noted that the study basin (Wilton Creek) is among the worst with respect to both potential gross erosion and sediment delivery ratio. The southernmost sub-basin (WC#3) is predominantly in row crops of corn and soybean with little or no buffer strips to prevent eroded soil from entering receiving streams. The Wilton creek sub-basin which was the subject of a monitoring program from 1988-1989 was located in a representation position of WC#3.

3.1.4 Water Quality

A water quality monitoring station was in place on Wilton Creek from 1965 to 1979. This station was located approximately 3.5 kilometres upstream from the creek mouth on Hay Bay where county road #8 crossed the creek. Water quality samples were taken once per month over the sampling period. Figures 3.4 to 3.6 characterize the water quality of Wilton Creek over the period of record. It is noted that no trend with time is apparent in the figures.

3.1.5 Wilton Creek Sub-basin

To assist in the development of the water quantity and quality studies, a sub-basin was selected in a corn growing area of the Wilton Creek basin (Figure 3.7) approximately 5 km from the gauged Napanee field (Section 3.2). The sub-basin consists of twenty one fields ranging in

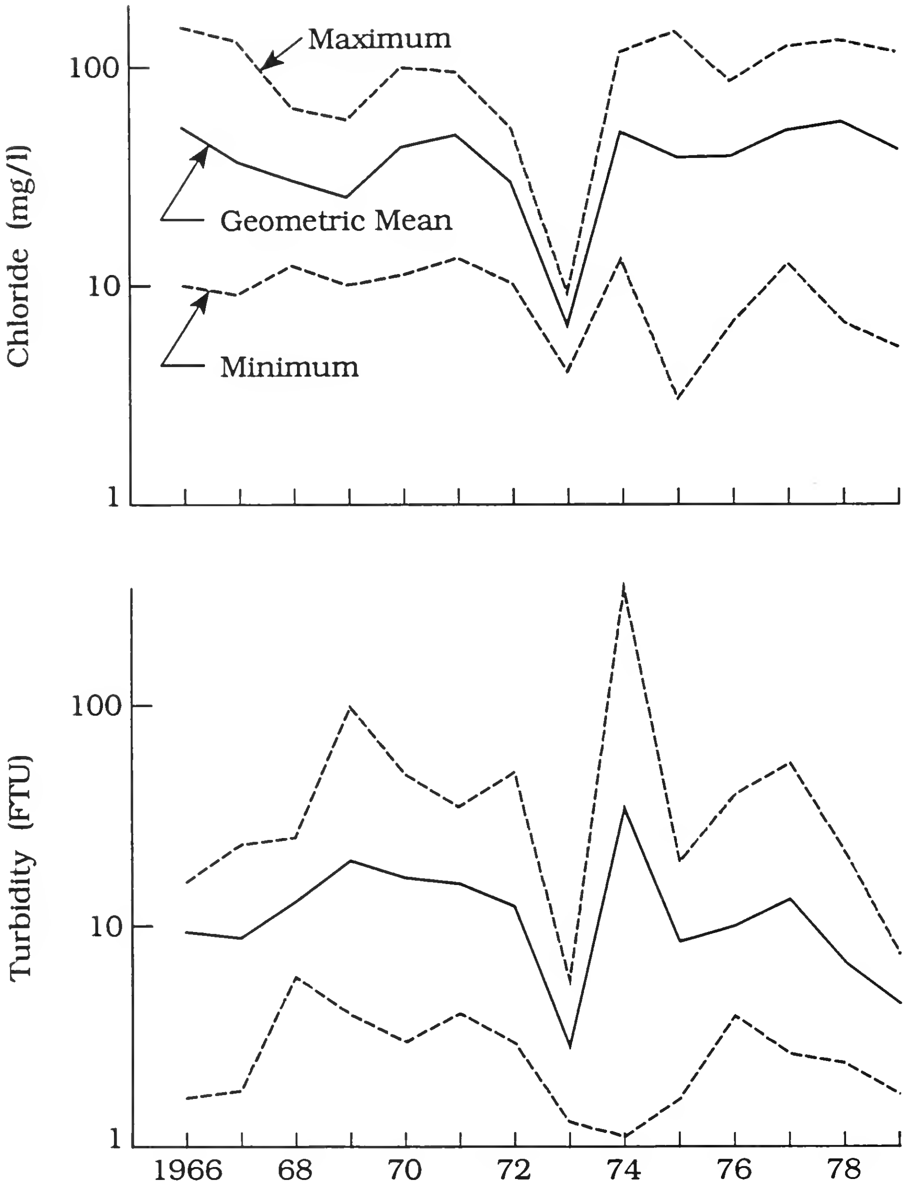


Figure 3.4 Chloride and turbidity time series - Wilton Creek

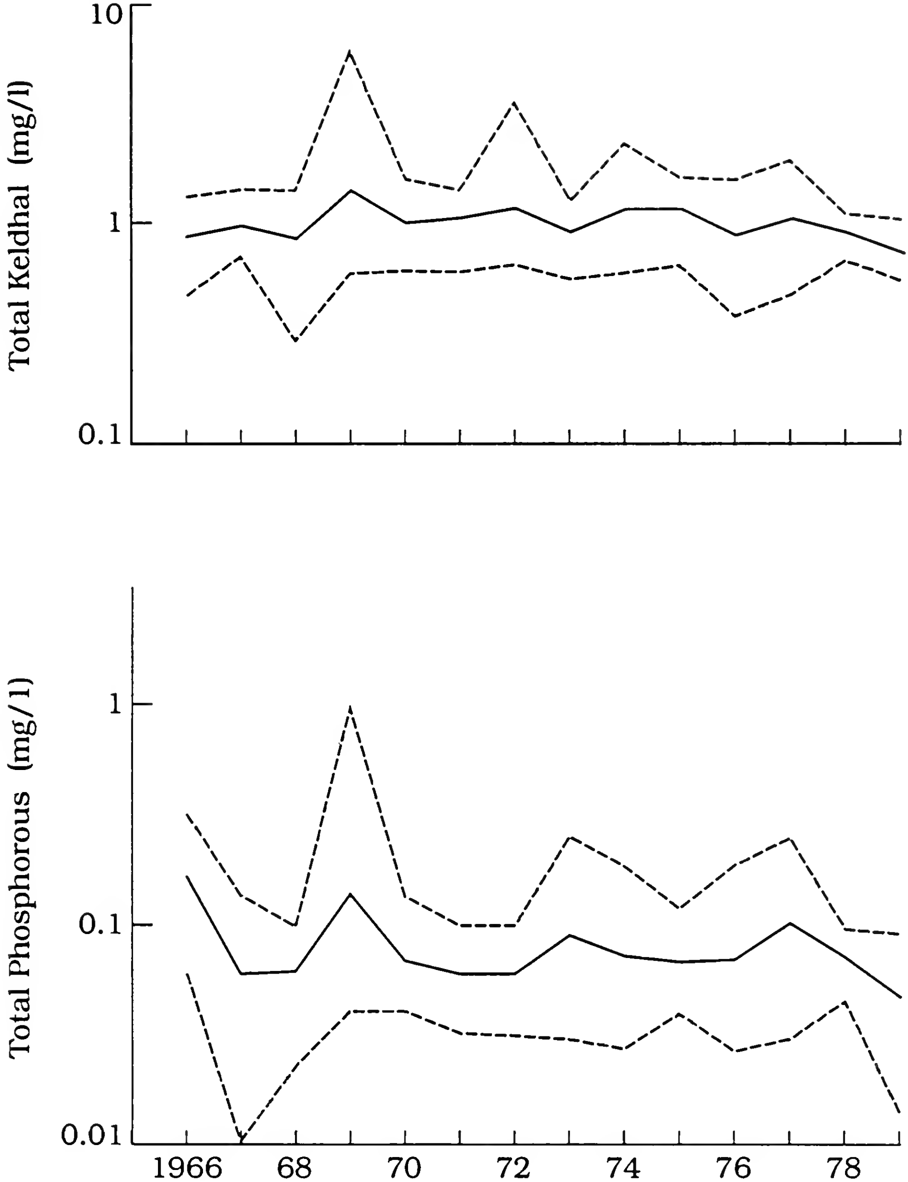


Figure 3.5 Nitrogen and phosphorous time series - Wilton Creek

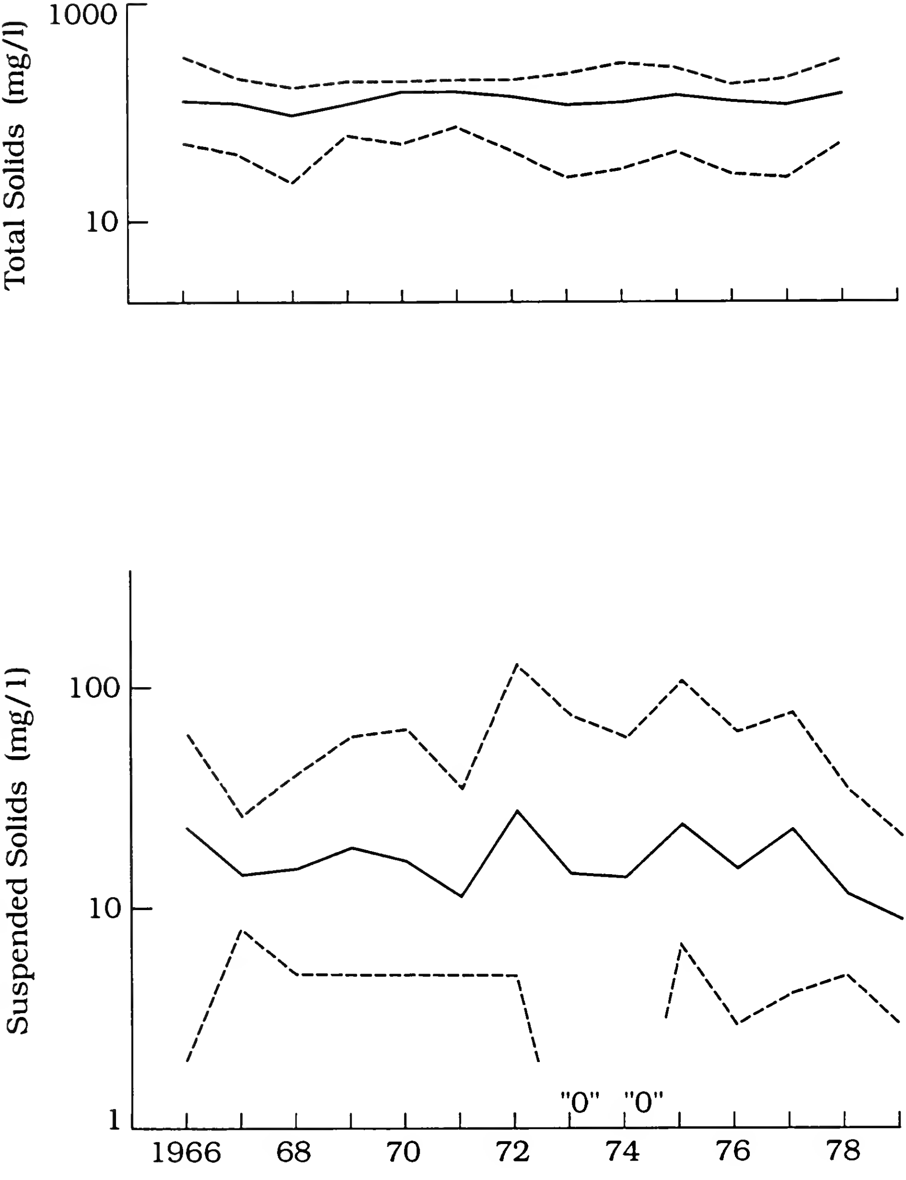


Figure 3.6 Total solids and suspended solids - Wilton Creek

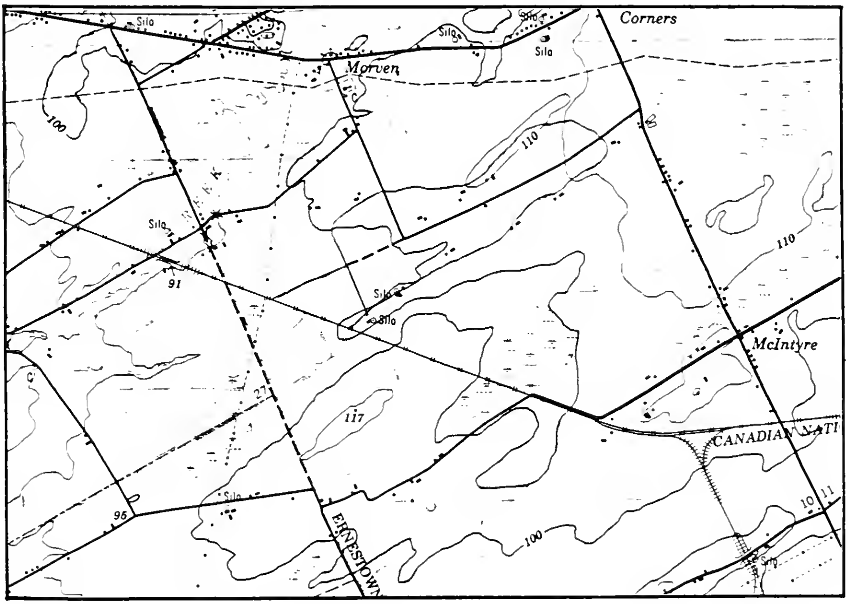


Figure 3.7 The Wilton Creek sub-basin

sub-basin has been improved by ditching to link the fields into an efficient drainage network.

To collect flow and quality data this sub-basin was instrumentated over the summer of 1989. A small weir was installed for water level control within a concrete box culvert on the water course. A tipping bucket rain gauge and Stevens A71 chart recorder were used to record rainfall and stage data. An Isco Model 2100 water quality sampler was installed to collect water samples under higher runoff events. Unfortunately only two very small hydrographs were recorded during the season.

3.2 Napanee Field

3.2.1 Physical Characteristics and Land Use

A field near Napanee, Ontario (Figure 3.8) was instrumented for rainfall and tile discharge as part of the previous project (152 PL). In 1987, the field experienced a crop rotation from corn to alfalfa. Although this change limited the utility of this field for this project, the instrumentation was maintained and in fact enhanced for the following reasons:

(i) to further enlarge the water quantity database, and

(ii) to detect any carryover from previous years of pesticides in the tile water.

In a subsequent section of this report, the necessity of an accurate simulation of water quantity processes in order to estimate water quality loadings is identified.

A topographic survey of the field (Figure 3.9) shows it to be gently sloped in a north-south direction with the slopes ranging from 0.0008 to 0.001. The limestone bedrock is not at a constant elevation under the field, but varies in depth from approximately 0.6 m along the northern edge to approximately 2.0 m at the southern end. The soil is a Lansdowne clay (Gillespie et al. 1963) overlying an Ordovician limestone. The tiles are spaced at 12.2 m and define a subsurface drainage area of 5.04 ha.

3.2.2 Instrumentation

Instrumentation on the Napanee field (Figure 3.10) included a collection tank with a

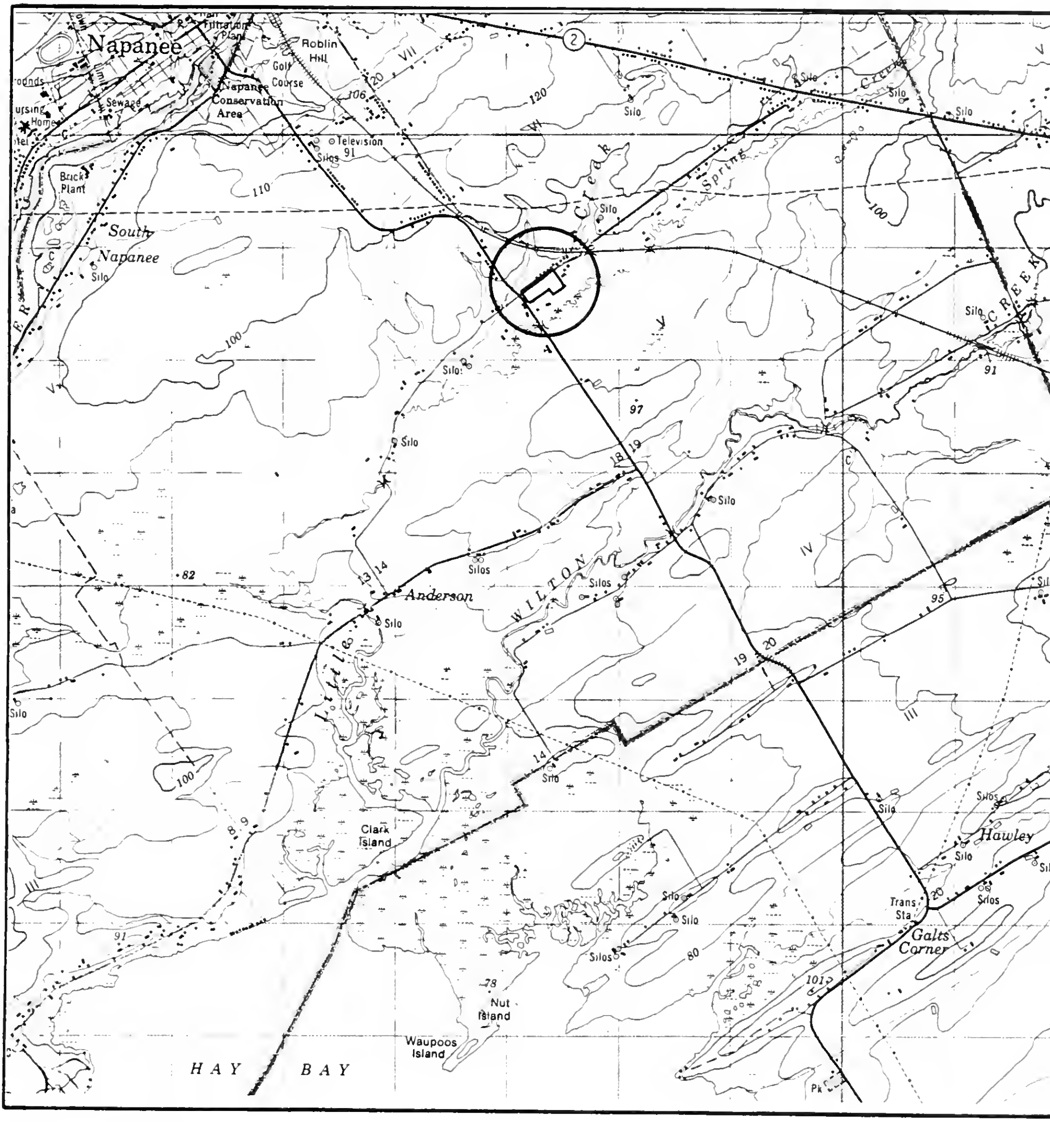


Figure 3.8 Location plan - Napanee field

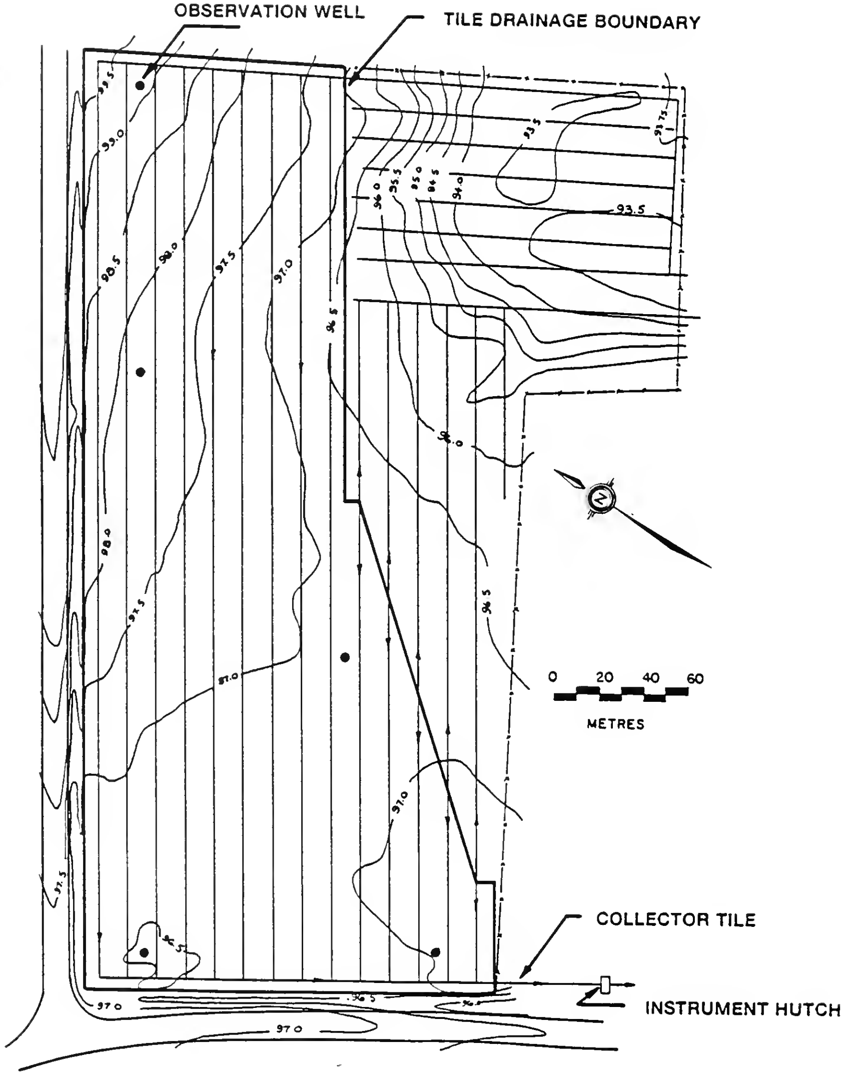
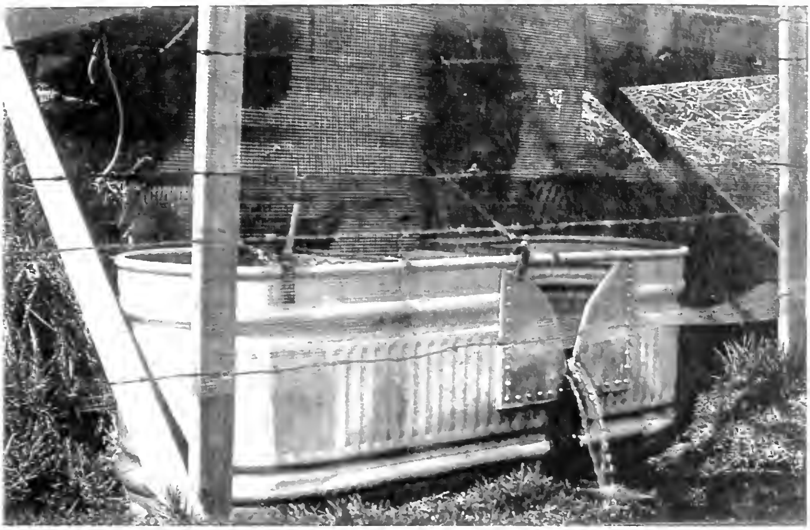
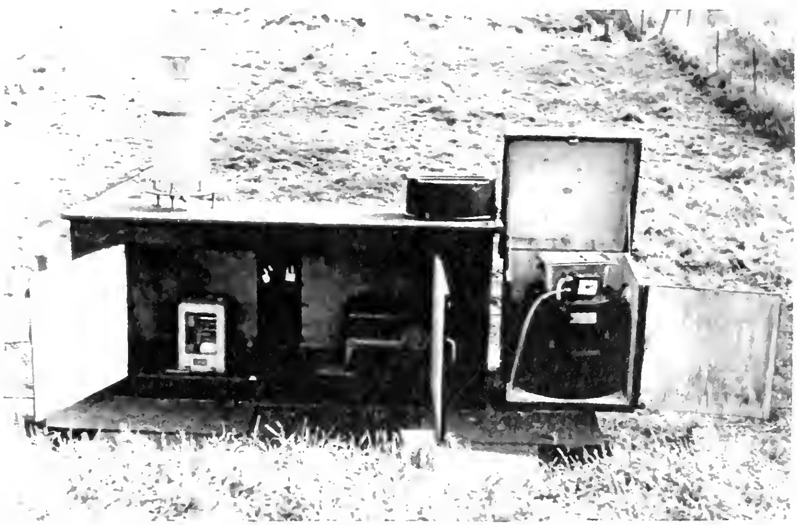


Figure 3.9 The Napanee field



Stock tank and V-notch weir



Tile discharge stage recorder, tipping bucket rain gauge and associated rainfall depth recorder and automatic water sampler

Figure 3.10 Instrumentation - Napanee field

compound V-notch weir at the tile outlet. Water levels over the weir were recorded continuously from April to December from 1986 to 1989 and from May to August 1990 with the use of a Stevens A-71 chart recorder at a 1:1 recording ratio and speed of 6.0 cm/day. Rainfall volumes and rates were recorded with a tipping bucket rain gauge and a continuous strip chart recorder (Weather Measure Corporation Model P522). Details on this instrumentation to 1989 are given by Whyte (1988) and by Paine and Watt (1988). A 24-bottle water quality sampler (ISCO Model 2100), modified to commence sampling once a threshold discharge from the tiled field was exceeded, was installed for the 1988 season.

3.2.3 Summary of Measurements

Rainfall and Water Quantity

Over the period of measurement, (1986-1990) about 20 discrete tile flow events (see Table 3.1) were measured.

Table 3.1 Tile flow-events - Napanee field

Year	Event Date	Comment
1986	Apr 15-21	
	May 19-23	Equilibrium tile flow & surface runoff
	June 11-16	Equilibrium tile flow & surface runoff
	Aug 8-11	
	Aug 15-18	Low tile flow
	Aug 27-30	
	Sept 10-16	Equilibrium tile flow & surface runoff
	Sept 22-28	Equilibrium tile flow & surface runoff
	Sept 29-Oct 6	Equilibrium tile flow
	Oct 12-Oct 16	
1987	Mar 21-28	
	Apr 1-10	
	June 7-10	Low tile flow
	Nov 3-10	Freezing weather
	Nov 17-Dec 5	Equilibrium tile flow
1988	Nov 20-23	Freezing weather, no rain data
	Dec 19-22	Freezing weather, no rain data

Year	Event Date	Comment
1989	May 2-13 June 20-28 Nov 7-11 Nov 14-24 Nov 27-30	Low tile flow Low tile flow Freezing weather Freezing weather Freezing weather
1990	Apr 10-13 Apr 20-23 Apr 24-27 May 17-20 May 21-23	Moderate tile flow Low tile flow Equilibrium tile flow and surface runoff Equilibrium tile flow and surface runoff Moderate tile flow

Water Quality

Pesticide application to the test field ceased in 1987 when the crop was rotated from corn to alfalfa. Some carry over of atrazene and its degradation byproducts was detected during grab sampling in 1987, however the lack of a spring application program effectively rendered the test field suitable for water quantity analysis only.

As a result of the lack of pesticide application on the Napanee field a search was intensified for alternate high quality field data on pesticide concentrations in tile flow. As a result of this search, data on fields maintained in Ottawa by Agriculture Canada were identified (Section 3.3).

3.3 Agriculture Canada Field

3.3.1 Research Agreement with Agriculture Canada

Following a conference presentation in 1987 on TILE, a simulation model developed under project #152 PL, Dr. N.K. Patni of the Animal Research Centre of Agriculture Canada contacted the writers regarding the possibility of co-operative research on tile-drained fields. As a result of subsequent visits to the Animal Research Centre in Ottawa and examination of research being conducted on pesticide application to tile-drained fields, a decision was made to enter into a co-operative research project. At this time, Dr. R.G. Warnock of the Department of Civil Engineering, University of Ottawa, was working with Dr. Patni on an investigation into

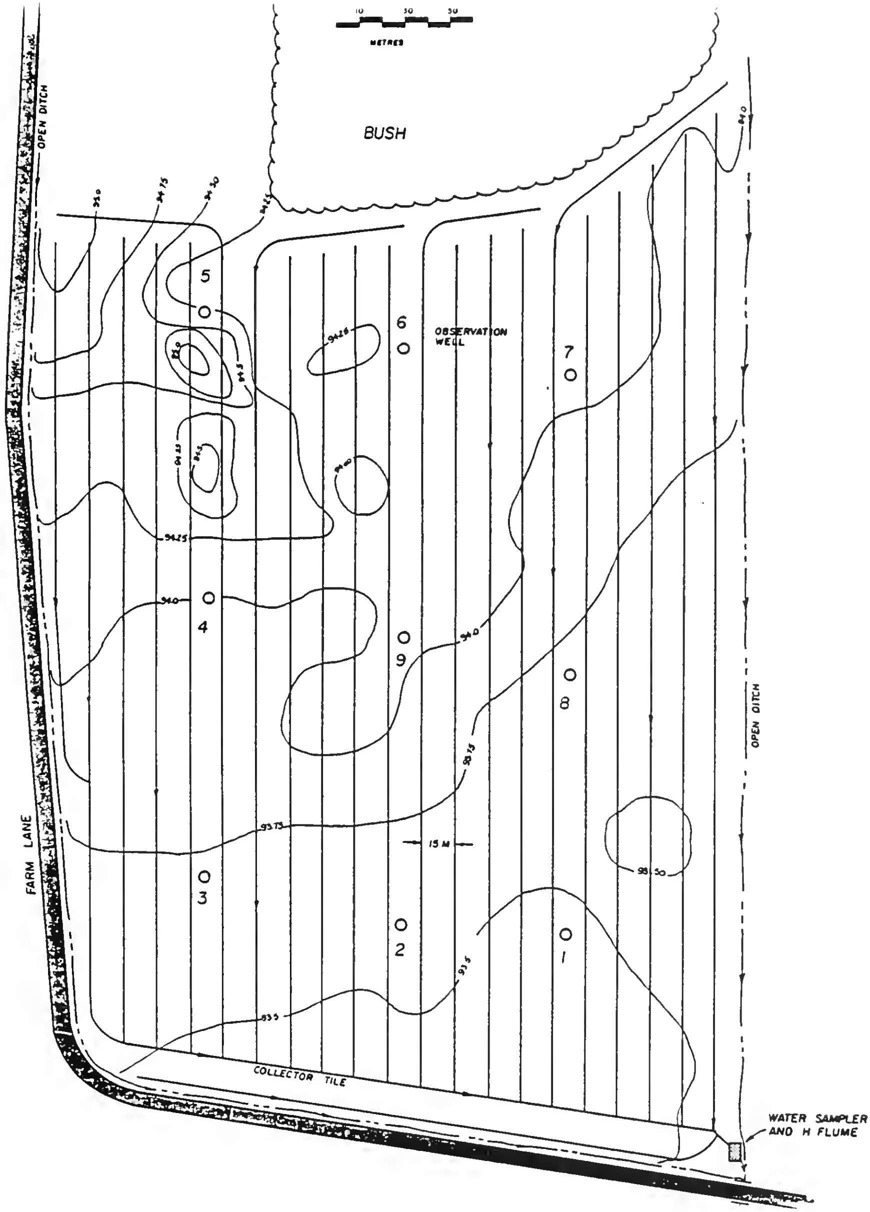


Figure 3.11 The Ottawa Field

the effect of macropores on tile drainage. Accordingly, an agreement involving participants from three establishments (ARC, Queen's University, and the University of Ottawa) was signed. The project title is "Modelling of Concentration Levels of Chemical Contaminants in Tile Drainage Flow". The project objective was "the development of methods whereby the concentration levels of chemicals applied to the soil surface can be predicted in the drainage". Project goals were:

1. Calibrate TILE, the Queen's University computer model for tile drainage flow, using existing data for selected fields in the ARC research farm.
2. Modify the computer model TILE for flow in the presence of macropores based upon laboratory data generated at the University of Ottawa.
3. Adapt revised model for water flow to the transport of chemicals using data to be collected at the ARC research farm fields."

With this opportunity for collection of high quality pesticide data in Ottawa, the focus of the research was altered following consultation with our liaison officer, Dr. Lloyd Logan. The change involved the use of the Ottawa field pesticide data in lieu of similar data from the Napanee field.

3.3.2 Physical Characteristics and Land Use

The study field is within the Greenbelt Farm of the Animal Research Centre of Agriculture Canada near Ottawa, Ontario. It was tile drained in 1986. During the study period for which site investigations were carried out, the field was planted in corn.

A topographic survey of the field (Figure 3.11) shows it to be gently sloped in a east-west direction with a mean slope of 0.0025, and a range of 0.0020 to 0.001.

The predominant soil types are Castor and Dalhousie clay loams overlying a marine clay. The tiles are spaced at 15.0 m and define a subsurface drainage area of 13.6 ha.

3.3.3 Instrumentation and Monitoring

Instrumentation on the Ottawa field included an H-flume at the tile outlet. Water levels on the H-flume were recorded continuously throughout the year from November of 1987 with the use of a Belfort chart recorder at a 5:12 recording ratio and a speed of 4.6 cm/day. Rainfall volumes and rates were recorded with a Belfort universal weighing bucket rain gauge. Water quality of the tile flow was sampled on an event basis using an ISCO 24-bottle water quality sampler. Groundwater levels were measured at nine sites on a continuous basis. Groundwater quality samples were taken at depths of 4, 6 and 10 feet at each site on an intermittent basis.

3.3.4 Field Tests

Saturated Hydraulic Conductivity

In the period July 18-21, 1989, Mr. Rob Adams, M.Sc. candidate in the Department of Civil Engineering at Queen's, and Mr. Lawrence Thooka, M.Sc. candidate in the School of Engineering at the University of Guelph, co-operated in an endeavour to determine the saturated hydraulic conductivity, K_s, of field no. 8. They used constant head Guelph permeameters to determine K_s at three depths (250, 500 and 800 mm) at each of nine sites.

Drainable Porosity

A field effective value of drainable porosity, μ, was obtained by dividing the depth determined by integrating the recession limb for the event of October 24-31, 1988 by the corresponding fall in water table elevation (see Taylor 1960).

Soil Water

In the period June-October 1989 Dr. R.G. Warnock, Professor of Civil Engineering, University of Ottawa, measured soil moisture content of field no. 8. He used a time domain reflectometry (TDR) device described by Topp et al. (1984) and Topp and Davis (1985) to determine soil moisture in the upper layer (0-200 mm) and a lower layer (200-400 mm) at each of the nine sites at weekly intervals.

3.3.5 Summary of Measurements

Rainfall, Water Quantity and Quality

Over the period of measurement (1987-1990), about 13 discrete tile flow events (see Table 3.2) were measured. At the time of writing, data for the latter half of 1989 and all of 1990 have been requested but not received from Agriculture Canada.

Table 3.2 Tile flow events - Ottawa field

Year	Event Date	Comment
1987	Nov 25-30	
1988	March 23-31 April 2-13 April 28-May 6 June 25-June 28 * July 1-July 5 * Oct 23-Oct 31 Nov 1-Nov 15	Snowmelt event Small tile flow event Good event Good event
1989	March 15-19 March 26-31 April 1-9 May 6-12 June 10-13	Snowmelt event Snowmelt event Small tile flow event Small tile flow event
1990		

* Water quality is available for only these events.

Groundwater Levels

Continuous groundwater level observations are available for the period Sept. 15 - Dec. 31, 1988.

Saturated Hydraulic Conductivity

The results of the investigations to determine hydraulic conductivity are given in Table 3.3.

Table 3.3 Hydraulic Conductivity (m/day) - Ottawa field

Site	Depth = 250 mm	Depth = 500 mm	Depth = 800 mm
1	0.39	0.29	0.22
2	0.07	0.11	0.07
3	0.16	0.02	0.03
4	0.24	0.15	0.01
5	1.17	2.91	0.14
6	0.87	0.08	0.003
7	0.15	0.21	0.02
8	0.06	0.10	0.03
9	0.04	0.01	0.03
Average	0.35	0.43	0.06

In reviewing this table, the following points should be noted.

- Sites 5 and 6 are located in an area with sandy topsoil not present in the rest of the field.
- With the exception of sites 5 and 6, the variability in hydraulic conductivity is that expected of a single soil type.
- The field average values of hydraulic conductivity for the upper two depths are virtually identical. The hydraulic conductivity at the lowest depth is an order of magnitude smaller. The presence of root systems, macropores and cracks in the soil and increased loam content may account for this difference.

Drainable Porosity

For the event analyzed, the depth of runoff of 7.2 mm coincided with a field-averaged water table drop of 244 mm. These figures indicate a drainable porosity of 0.03.

Table 3.4 Average soil water content (%) - Ottawa Field

Date		Upper Layer 0 - 200 mm	Lower Layer 200 - 500 mm
June	13	34	34
	20	35	35
	27	31	32
July	4	24	28
	11	26	27
	18	18	24
August	1	18	23
	8	20	23
	15	16	21
	22	18	17
	29	15	20
Sept.	13	20	23
	20	20	22
	27	24	27
Oct.	4	27	27
	11	27	27
	18	32	20
	25	32	25
Nov.	1	33	36
Nov.	8	35	37

Table 3.5 Soil water content (%) - Ottawa Field, June 13/89

Site	Upper Layer 0 - 200 mm	Lower Layer 200 - 500 mm
1	33	36
2	38	39
3	40	35
4	33	27
5	20	23
6	36	33
7	35	36
8	35	41
9	38	34
Average	34	34

In reviewing this table, the following points should be noted.

- As indicated earlier, site 5 is located in an area with sandy topsoil not present in the rest of the field.
- Within the exception of site 5, the variability in soil water content is very small.

Soil Water

The results of the investigations to determine soil water are presented in two tables. In Table 3.4, measured values of field-averaged soil water content at weekly intervals for the period June - November 1989 are given. The higher values of soil water content may be used to assist in estimating the field capacity which is particularly important in defining the hydrologic response of a tile-drained field.

It should be noted that the values given in Table 3.4 are averages for the field. Some indication of the variation within the field is provided by Table 3.5 which displays the measurements at nine sites for the June 13 data set.

4.0 SIMULATION MODEL FOR TILE DRAINAGE QUANTITY AND QUALITY

4.1 Modelling Considerations

Q-TILE is a physically-based model designed to simulate the hydrologic responses of an agricultural field subjected to tile drainage. Flow processes modelled are infiltration, filling depression storage, percolation of infiltrated water into the root zone and the lower zone, groundwater flow and evapotranspiration from the soil surface and lower zone. Contaminant processes modelled are solution, oxidation and transport on the surface, mixing processes and degradation within the soil water, and adsorption and washoff at the soil-water interface.

One of the primary considerations during the development of the model was the desire to maintain a balance between the complexity in describing the physical processes and the accuracies possible in measuring the physical characteristics and parameters of the prototype fields. Accordingly, the following considerations were deemed important.

- The model should be modular and decomposed into physically separable components
- The model algorithms should be as simple as possible, with additional complexities introduced only where required and as justified by field measurements.
- The model should contain a minimum number of parameters requiring calibration.
- Where possible, parameters should be physically based (i.e. measurable independent of the model) and determinable with a minimum of field effort.
- The model should be capable of simulating short time steps for accurate assessment of surface flow, tile flow and contaminant loadings.
- The model should be robust and capable of accurate simulation for a range of soil types, tile configurations, nutrient and pesticide inputs.

4.2 Water Quantity Submodel

4.2.1 Overview of Physical Processes

TILE, which is described in detail by Paine and Watt (1988), is a physically-based deterministic model, simulates on an hourly basis, the hydrological responses of an agricultural field subjected to tile drainage. Figure 4.1 illustrates the systematically tile drained field which

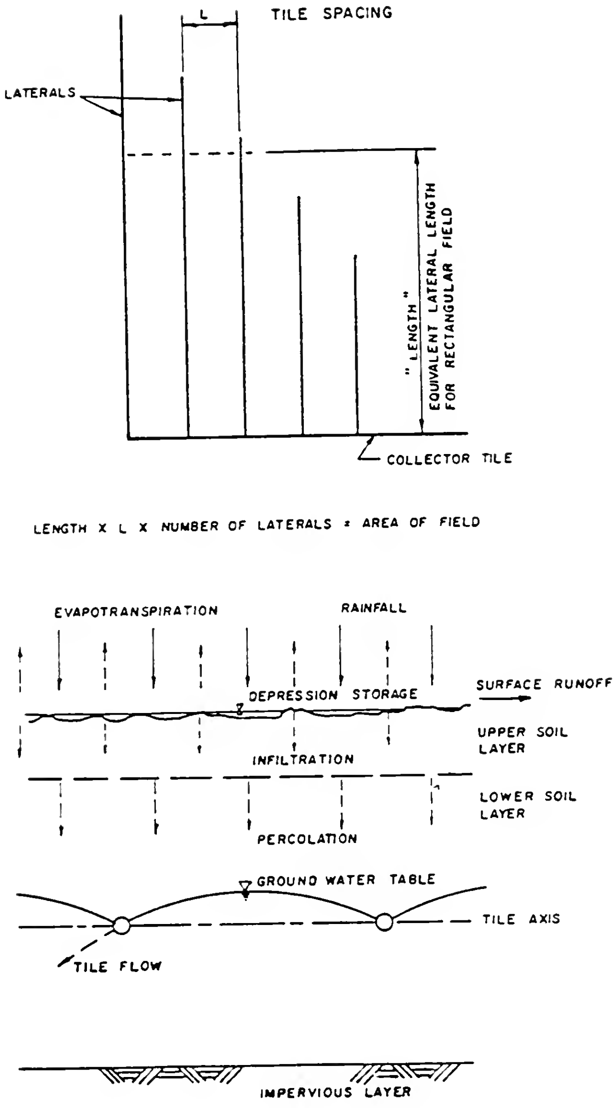


Figure 4.1 The physical system - a systematically tile drained field

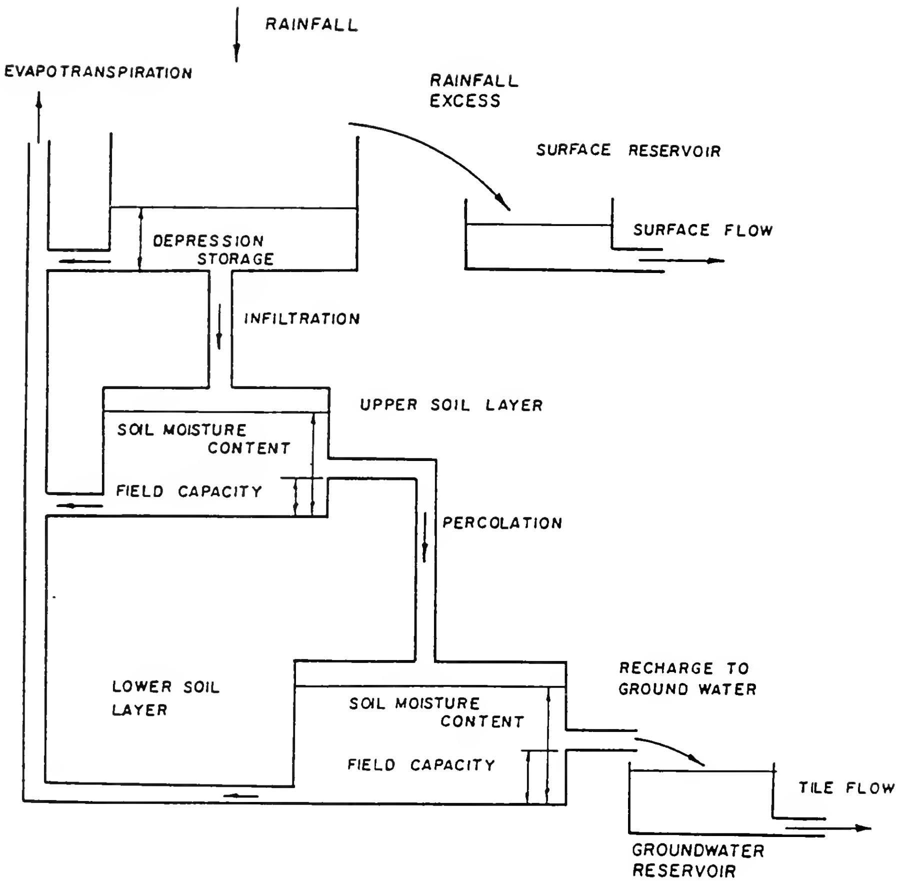


Figure 4.2 Conceptual representation of physical system

TILE is capable of modelling. Also illustrated is the method of defining an equivalent tile lateral length for situations where the systematic drainage has varying tile lengths. The model is not suited for accurately modelling random or dendritic type drainage schemes.

As in any conceptual model replicating a hydrologic system, the natural system may be represented by storage elements linked with transmission elements. Figure 4.2 illustrates this representation of the real system by the model.

The storage elements include:

i) surface storage which includes storage in depressions and temporary storage providing the driving head for surface runoff,

ii) upper zone soil water storage which represents water storage in the ploughed layer,

iii) lower zone soil water storage which represents water stored between the bottom of the ploughed layer and the tile axis, and

iv) regional groundwater storage which represents groundwater stored below the tile axis.

Transmission elements include:

i) routing of surface flow to the edge of the field,

ii) infiltration to the upper soil water zone,

iii) percolation from the upper zone to the lower zone,

iv) evapotranspiration from the soil water storage,

v) recharge to groundwater, and

vi) discharge from the lower zone via the tile drainage system.

4.2.2 Surface Submodel

Rainfall arriving at the field surface first enters a surface reservoir. Outflow from this reservoir can occur through infiltration, evapotranspiration and surface runoff. Part of this surface reservoir represents depression storage and the filling of depression storage is part of the surface submodel.

The remainder of the surface reservoir represents detention storage. The rainfall excess is routed through this detention storage to yield surface runoff at the edge of the field. The

surface routing process is modelled by a single linear reservoir whose time constant depends on the length and slope of the field.

4.2.3 Soil Water Submodel

Soil water storage is considered in two distinct zones, an upper zone or root zone typically 200-400 mm in thickness and a lower zone between the upper zone and the tile axis. Soil water storage in the upper zone is treated independently of that in the lower zone unless the groundwater table enters the upper zone (lower zone saturated). Prior to any percolation into the lower zone, the field capacity of the upper zone must be filled. With the field capacity full, percolation into the lower zone is related to the soil water in the upper zone; water content in the upper zone is increased by infiltration and is decreased by percolation and evapotranspiration. The upper soil zone may become saturated in spite of unsaturated conditions in the lower zone.

Infiltration is limited by either the rainfall rate or the infiltration capacity. Infiltration capacity is calculated from an equation suggested by Holtan (1961) whereby the soil water content in the upper zone and soil characteristics dictate the infiltration capacity.

Water content in the lower zone is increased by percolation from the upper zone and decreased by drainage to the tiles and evapotranspiration.

Percolation occurs when the soil water content in the upper zone exceeds field capacity. It varies linearly from zero to saturated hydraulic conductivity as a function of water content in excess of field capacity.

A groundwater table (above the tile axis) is defined if the field capacity in either the upper zone or the lower zone is exceeded. In this event, the groundwater table elevation is related to the soil water content through the drainable porosity.

4.2.4 Tile Flow Submodel

Inflow to the tiles is computed using an expression developed by Hooghoudt (1940) and modified by Moody (1966). This inflow is a function of the water table height (above the tile axis), physical parameters and tile characteristics which are constant for a particular installation. The parameters are saturated hydraulic conductivity and equivalent depth to the impervious

layer. Tile characteristics are spacing and diameter.

Tiles are assumed to be of adequate capacity and travel time in the tile is assumed to be negligible so that tile discharge is identical to tile inflow.

4.2.5 Evapotranspiration Submodel

Evapotranspiration is simulated from the surface storage and upper and lower soil water zones. As a first step, potential evapotranspiration is treated as a demand and is calculated in one of three ways: (i) from pan evaporation observations (ii) using Thornthwaite's equation (Thornthwaite 1948) or (iii) using the approach proposed by Priestley and Taylor (1972) approach. Then, actual evapotranspiration is simulated from the surface reservoir, the upper soil zone and the lower soil zone in that order in an attempt to meet the demand.

Evaporation from the surface reservoir takes place at the maximum potential evapotranspiration rate (water unlimited). Evapotranspiration from the soil layers takes place at the maximum potential rate as long as the water content is greater than 60 percent of the saturated value. For lower values of soil water the actual evapotranspiration rate is linearly related to the soil water content.

4.3 Water Quality Submodel

4.3.1 Overview

The modelling philosophy employed in development of the TILE quantity submodel provided for expression of a complex system (drainage hydrology) in a simplified fashion through consideration of a minimum number of physically measurable parameters. This modelling approach, which required that all model parameters be physically based and as simple as possible, was also employed for the development of the water quality submodel.

To successfully represent the complex interactions within the environmental compartment consisting of a single tile drained agricultural field in the first generation model, only those processes considered to be most significant were included. Those processes were expressed in the simplest possible manner using algorithms based on physically measurable parameters. Refinements, if required to reduce discrepancies between physical observations and model

output, would be introduced during development of later generation models.

The limitations of this modelling exercise include accuracy of measurement of the physical parameters employed, simplification of complex processes through lumping of coefficients, and limitations to the existing knowledge of the properties and behaviour of agricultural chemical constituents.

The migration of chemical constituents in agricultural systems may be mathematically modelled through consideration of the general partial differential equation for mass transport as it applies to solute transport in saturated porous media. The advection-dispersion equation for solute transport in saturated porous media can be expressed in mass balance equations of the form:

$$M_t = M_{t-\Delta t} + M_{in} - M_{out} + M_{reaction}$$

which can be written for each of the storage reservoirs and for the whole system of a single tile drained agricultural field, as shown in Table 4.1. The resulting equations can be linked to form a mathematical model for constituent mass conservation which is driven by the physically based hydrologic transport model.

4.3.2. Submodel Structure

Figure 4.3 illustrates the field level processes making up the physical system modelled by Q-TILE (TILE modified to include water quality). The conceptual representation of chemical constituent migration within the framework provided by the hydrologic model is shown on Figure 4.4.

The model control volume is a single tile drained agricultural field. Water is input to the field as precipitation and exits by evapotranspiration, tile flow or surface runoff. Chemical constituent mass is input to the field by human application and is allowed to leave the control volume carried by tile flow and/or surface runoff and through a generalized loss function

replicating the effects of a number of chemical, physical and biological transformation processes.

Within the model control volume, chemical constituent mass storage is represented by the following three storage elements:

i) a surface storage reservoir from which the constituent may leave the system carried by surface runoff or enter the soil storage reservoirs along with infiltration water,

Table 4.1 Mass balance equations for a tile drainage system

FOR ALL CONTROL VOLUMES (STORAGE RESERVOIRS) $M_t = M_{t-\Delta t} + M_{in} - M_{out} + M_{reaction}$			
RESERVOIR	M_{in}	M_{out}	$M_{reaction}$
Depression (surface) storage	Chemical input (application to field)	Surface flow Infiltration	Plant interception Photolysis Volatilization Chemical reaction
Upper soil layer storage	Infiltration	Percolation	Plant root interception Adsorption Chemical reaction Microbial degradation
Lower soil layer storage	Percolation	Tile Flow	Adsorption Chemical reaction Microbial degradation
Whole single field system	Chemical input (application to field)	Surface flow Tile flow	Plant interception Photolysis Volatilization Chemical reaction Plant root interception Adsorption Microbial degradation

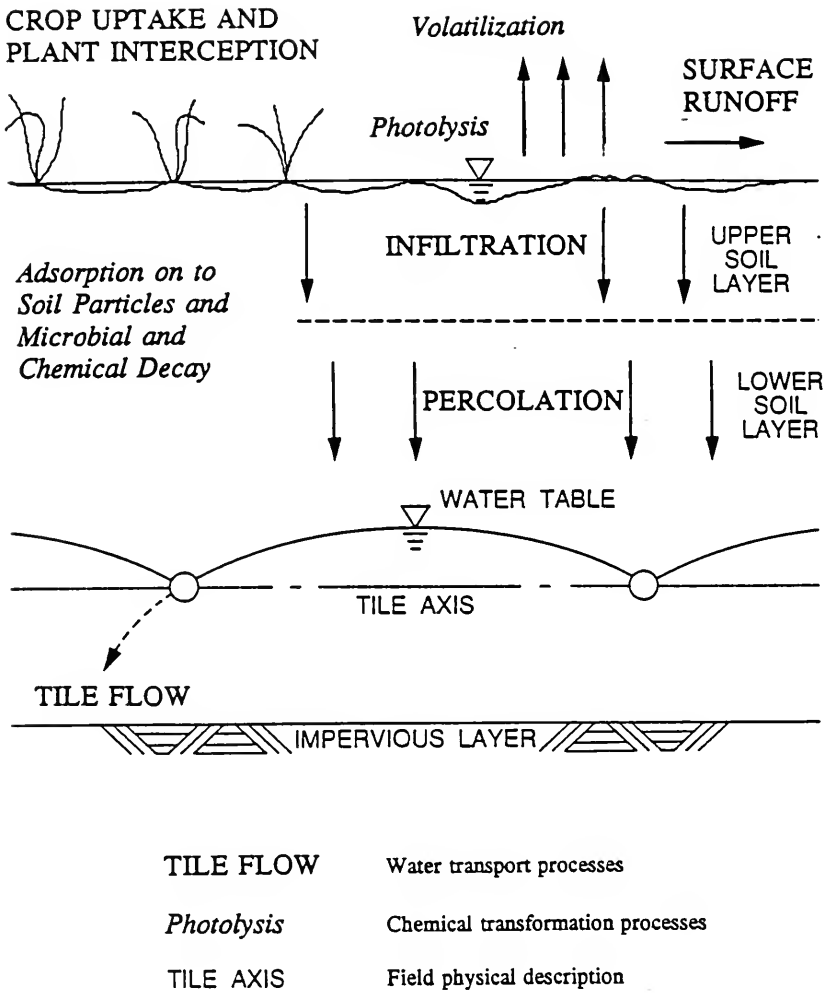


Figure 4.3 Field level processes affecting chemical constituent fate

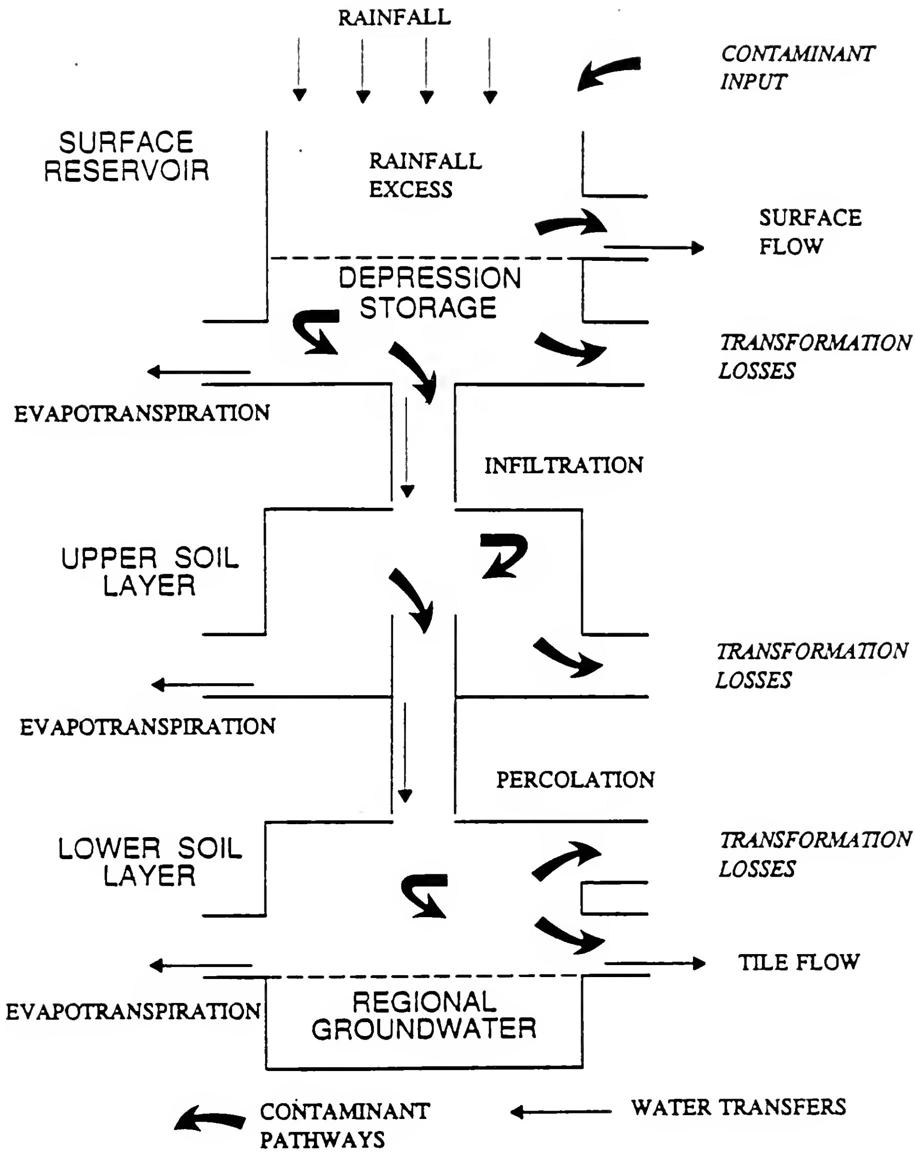


Figure 4.4 Conceptual representation of chemical constituent migration

ii) an upper soil layer storage reservoir from which the constituent may enter the lower soil storage reservoir through percolation, and

iii) a lower soil layer storage reservoir from which the constituent may be discharged from the system through tile drainage.

The constituent mass transmission pathways linking the three storage elements are:

i) application of the constituent mass to the field,

ii) transport of the constituent mass to the edge of the field by surface flow and subseqent loss of the mass through the control volume boundary,

iii) migration of the constituent mass from the surface mass storage reservoir to the upper soil layer carried by infiltration water,

iv) migration of the constituent mass from the upper soil layer storage reservoir to the lower layer carried by percolation water, and

v) routing of the constituent mass to the tile drains and subsequent loss of the mass through the control volume boundary carried by tile flow.

The quality submodel allows for application of a transformation or reaction function to the constituent mass as shown in Figure 4.4. This function represents a number of physical, chemical and biological processes, as summarized in Table 4.1, which act within the agricultural field system to reduce the constituent mass available for transport to all three of the mass storage reservoirs. The most significant processes lumped within the representative transformation function are:

i) dispersive or turbulent flow distortions to advective constituent transport,

ii) constituent adsorption onto soil particles,

iii) physical transformation processes such as photolysis or volatilization,

iv) chemical transformation processes including hydrolysis and other chemical reactions, and

v) biological transformation processes such as microbial decay and plant interception.

4.3.3 Constituent Transport Algorithms

In order to integrate the conceptualization of constituent mass migration presented in Figure 4.4 into the computational framework provided by the existing TILE model, an algorithm were formulated which used the quantities of water transferred between storage reservoirs by TILE to predict the constituent masses to be transferred between analogous mass storage reservoirs. Within each timestep, the water transfers are abstracted from TILE and a computational protocol is applied to simulate mass transfers between reservoirs and calculation of new mass concentrations. In each case, the mass transferred is dependent upon the volume of water transferred and upon the constituent concentration of the upstream reservoir. Thus, if no water is transferred between storage reservoirs, it is assumed that no mass is transferred.

The mass transport algorithm outlined above includes two important simplifying assumptions. The first is that mixing within the storage reservoirs is complete within a single computational timestep. Thus, water and constituent mass entering a soil storage zone from the top are considered to mix completely with the water and mass already present in that soil zone within the timestep and may leave the soil zone through the bottom by the beginning of the next timestep. The second simplifying assumption is that mass transfers between storage reservoirs are instantaneous.

The computational protocol applied to simulate mass transfer in the TILE water quality submodel is summarized in Table 4.2.

In order to represent the physical system of an agricultural field and the behaviour of specific chemical constituents more accurately, four factors: the constituent application method, the timing of the constituent application, the solubility of the chemical in water and a field-specific chemical mobility threshold were incorporated into the TILE water quality submodel.

Constituent Application Method and Timing

The Guide to Weed Control produced by the Ontario Ministry of Agriculture and Food (1988) indicated that the methodologies by which agricultural chemicals, including fertilizers and

pesticides, were applied to farm fields could be divided into two categories:

1. surface application, in which the chemical is placed onto the soil surface as a liquid spray or broadcast of solid pellets, and
2. incorporation, in which the chemicals are incorporated into the upper layer of the soil itself by tilling.

Incorporation methodologies are increasing in popularity because they are believed to reduce post-application losses due to wind action, surface runoff and transformation processes such as volatilization and photolysis.

Table 4.2 TILE computational protocol for constituent mass migration

COMPUTATIONAL STEP	DESCRIPTION
1	Storage reservoir constituent concentrations are calculated based on the constituent mass and the volume of water within each reservoir at the beginning of the computational timestep.
2	Constituent masses lost to the surface storage reservoir are calculated based the TILE infiltration and surface flow rates and the constituent concentration of the surface storage reservoir.
3	The constituent mass lost to the upper soil storage reservoir through percolation to the lower soil layer is calculated based on the TILE percolation rate and the constituent concentration of the upper soil storage reservoir.
4	The constituent mass lost to the single field system through generation of tile flow is calculated based on the TILE tile flow rate and the constituent concentration of the lower soil storage reservoir.
5	Calculated constituent masses are transferred between storage reservoirs to update constituent mass balances for the beginning of the next computational timestep.

To allow for simulation of the impact of application of a variety of agricultural chemicals in realistic use scenarios with the TILE model, the application method is specified by the user in conjunction with the time of application. If a surface application method is indicated, the program assigns the input mass to the surface storage reservoir. If, however, an incorporation method is specified, the input mass is assigned directly to the upper soil storage reservoir. The timestep during which the chemical constituent is exposed to the action of transport and transformation processes is controlled by the input application timing.

Chemical Solubility and Mobility Threshold

Agricultural chemicals, especially pesticides, that are commonly applied to farm fields are often formulated as solids or wettable powders with widely varying solubilities, or as liquids with low solubilities in water. To attempt to model the behaviour of undissolved or partly dissolved chemical species, two modifications were incorporated into the TILE quality submodel.

The first modification allows the user to input a laboratory or field-corrected solubility in water for the chemical constituent of interest. Laboratory solubilities are easily obtained from the literature for most agricultural chemicals. The model responds to the input solubility value by limiting the amount of chemical dissolved in the water available in a specific reservoir. This limitation is currently applied only when the constituent is intially added to the system and thus the first generation model does not allow for later precipitation of the constituent.

In addition to the chemical solubility in water, review of the physical system of an agricultural field indicates that there will be a limiting quantity of water below which it is unlikely that a chemical could be dissolved and mixed instantaneously within a particular storage reservoir. The large surface area of agricultural fields, in combination with the fact that the surface storage and upper soil zone storage reservoirs represent three-phase systems consisting of soil, soil water and air voids, suggests that there exists some minimum quantity of water capable of actual movement of a chemical constituent. This minimum water quantity is referred to as a mobility threshold.

The quality submodel allows for consideration of a separate mobility threshold for each of the two categories of chemical application methodologies. If surface application is specified, the mobility threshold corresponds to a minimum depth of water present in depression storage as a result of precipitation inputs to the system. Thus, it is possible for a small amount of rain to fall upon the field and infiltrate into the upper soil storage reservoir without resulting in the transfer of any chemical mass. If, however, incorporation application is chosen, the mobility threshold requires that the specified volume of water be present above the field capacity moisture content within the upper layer soil storage reservoir for solution, mixing and transfer of the chemical constituent to occur.

4.3.4 Constituent Transformation Algorithms

Consideration of the transformation processes acting on agricultural chemicals to reduce the concentrations of those chemicals available for transport indicates that their interactions within a single field agricultural system are extremely complex. It is very difficult to separate the effects of different processes and the literature contains few attempts to quantify the effects of individual processes. For these reasons, these transformation processes are represented in the first generation model by a lumped transformation coefficient.

It is likely that a difference exists between surface and soil chemical transformation processes because different processes will be more significant in different constituent storage reservoirs. In some reservoirs, certain processes will not apply at all. For example, photolysis is not applicable to chemical masses protected from the sun within the soil layers. In addition, microbial degradation of chemical constituents will not be significant in the surface storage reservoir which contains few microorganisms.

The quality submodel allows for distinction between the lumped processes assumed to be significant in the surface storage reservoir and those in the soil storage reservoirs through application of different loss coefficients, specified by the user, to the different reservoirs. These coefficients are employed in first order relationships to calculate masses lost from each field storage reservoir and masses remaining during each timestep.

In the absence of field surface and soil retention studies for specific chemical constituents subject to specific transformation processes, it is suggested that transformation process coefficients be inferred from literature values for constituent half lives. For first order transformation processes,

$$m_t = m_o \, (k_r)^t$$

where m_t is the constituent mass present at time t, m_o is the initial constituent mass present and k_r is the rate constant. As defined in the Q-TILE program, the transformation process coefficient, k_{tp}, is given by $1 - k_r$. Thus, when t is the half-life, $t_{½}$, and $m_t / m_o = 0.5$,

$$k_{tp} = 1 - k_r = 1 - (0.5)^{t_{1/2}}$$

4.4 Input Requirements and Output Provided

4.4.1 Input Requirements

Input for the Q-TILE program is contained in five files:

(i) a field file which contains the physical characteristics and soil parameters of the tile-drained field

(ii) a rainfall file which contains the rainfall time series (hourly increments);

(iii) an evapotranspiration file which, depending on the method used, contains pan evaporation, temperature or solar radiation (each on a daily basis);

(iv) a contaminant file which contains the application method, timing, and loadings of the chemical of interest as well as estimates of quality parameters; and

(v) an optional flow file which contains observed tile flows (hourly intervals).

4.4.2 Output Provided

Output for the Q-TILE program can take the following forms:

(i) an optional echo check of the data entered in the field file,

(ii) a field water balance for the period simulated,

(iii) rainfall, flow and water table time series (in tabular form)

(iv) soil water time series (in tabular form),

(v) a field contaminant balance for the period simulated, and

(vi) contaminant time series for surface reservoir, soil water, tile water and losses from the system.

4.5 Model Characteristics and Parameters

A model testing procedure was applied to the water quality model to assess its response to variation in input parameters. At present, a comprehensive data set suitable for rigorous model calibration, including measurements of rainfall, tile flow, and surface flow volume, soil water content, chemical constituent application mass and timing, and constituent concentrations in soil and tile and surface runoff, is not available. In the absence of calibration data for the quality submodel, the model was applied using calibrated water quantity parameters and water quality parameters selected from the literature to investigate model response.

4.5.1 Quantity Model

The quantity model was calibrated for the two fields described in chapter 3 and the Leclerc field near Casselman which is described in Paine and Watt (1988). Because water transports contaminants, the ability of the model to simulate tile flow accurately is of paramount importance. Accordingly, earlier calibrations for the Napanee and Leclerc fields were updated in light of additional data and minor changes to the model.

Field characteristics and values of parameters resulting from calibration are given in Tables 4.3 and 4.4.

Table 4.3 Field characteristics for test fields

	Field		
Characteristic	Napanee	Leclerc	Ottawa
Diameter of tile laterals, mm	100	100	100
Tile spacing, m	12.2	16.8	15.0
No. of rows of laterals	14	16	21
Equivalent length of tile laterals, m	297	549	445
Depth upper layer, mm	300	300	300
Depth lower layer, mm	700	700	700

Table 4.4 Parameters for test fields

	Field		
Parameter	Napanee	Leclerc	Ottawa
Hydraulic conductivity, m/d	0.4	1.0	0.5
Drainable porosity	0.02	0.10	0.03
Depth to impermeable layer from drain axis, m	1.0	0.85	1.0
Maximum depression storage, mm	2	10	2
Ultimate infiltration capacity mm/h	5.0	9.0	5.0
Vegetation parameter in Holtans equation	0.3	0.1	0.3
Field capacity upper layer	0.25	0.17	0.26
Field capacity lower layer	0.45	0.17	0.40

Use of the characteristics and parameters displayed in Tables 4.3 and 4.4 resulted in simulated hydrographs that matched observed hydrographs quite closely. One example for each field is displayed on Figures 4.5, 4.6 and 4.7.

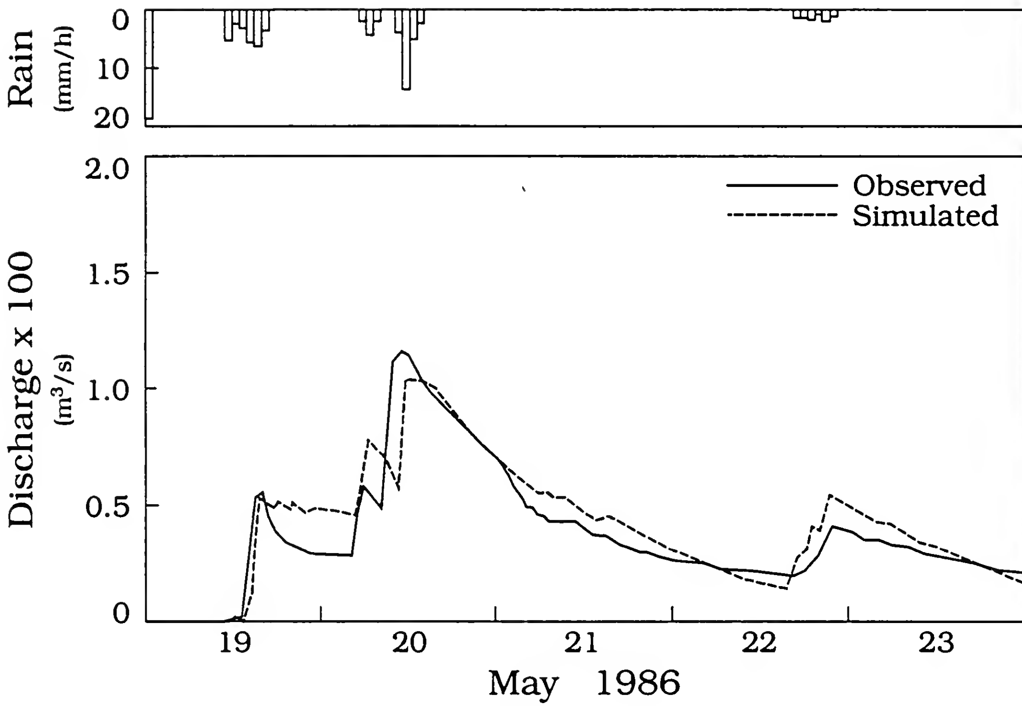


Figure 4.5 Observed and simulated hydrographs - Napanee field

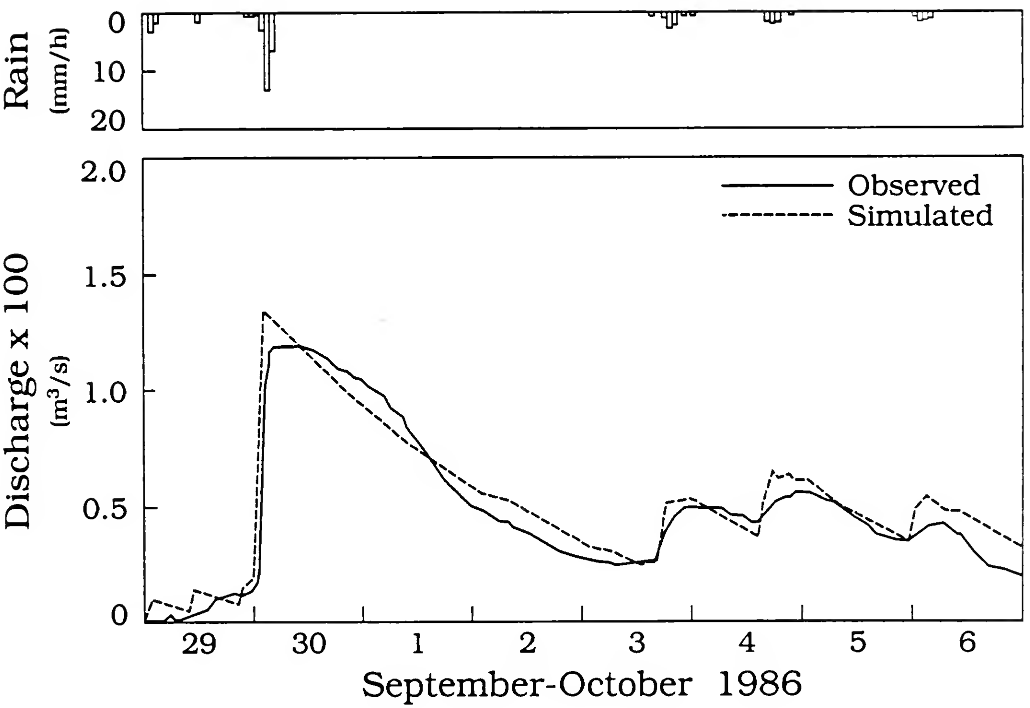


Figure 4.6 Observed and simulated hydrographs - Leclerc field

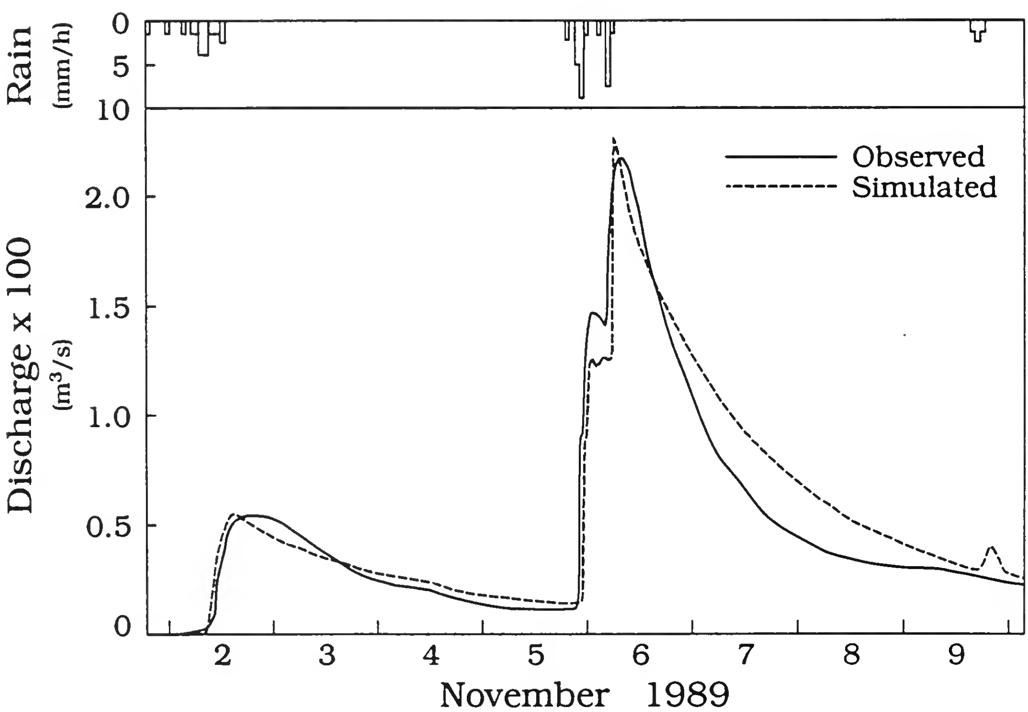


Figure 4.7 Observed and simulated hydrographs - Ottawa field

4.5.2 Quality Model

Table 4.7 details the water quality submodel input data required for chemical constituent fate simulation with the TILE model, along with possible data determination methods. The water quality data requirements are grouped into two categories: constituent characteristics and model parameters.

The constituent characteristics are defined by the simulation scenario considered and include initial constituent masses for each of the mass storage reservoirs, the timing, mass and method of constituent application to the field and constituent specific properties such as the solubility. The inclusion of initial constituent masses in the model input allows the user to simulate the effects of the presence of constituent masses applied to the field during a previous growing season.

Model parameters depend on the interaction between field characteristics and chemical constituent properties and are potentially calibratible. For the first generation Q-TILE model, the model parameters are the lumped constituent transformation coefficients for ground surface and soil processes and the field mobility threshold. Constituent transformation coefficients may be estimated directly from laboratory or field soil retention studies performed for the constituent of interest or inferred from literature descriptions of the constituent response to the processes hypothesized to be significant in each of the storage reservoirs. The field mobility threshold represents the rainfall or soil water content below which the nature of the agricultural field system indicates that it is unlikely that the constituent would be mobile in soil water. This threshold is likely dependent on both the field soil characteristics and on the chemical constituent of interest and in the absence of field studies, must be estimated from field characteristics and chemical constituent properties.

Table 4.5 Water quality submodel input data for chemical constituent fate simulation

INPUT DATA TYPE	CHARACTERISTIC OR PARAMETER	DETERMINATION METHOD
Constituent Characteristics		
Initial constituent mass	initial constituent mass in surface upper soil layer and lower soil layer storage reservoirs	• output from previous simulation • laboratory analysis of surface soil samples • chemical retention estimation from literature
Constituent application data	constituent application mass, timing and method	• consultation with farmer
Constituent properties	constituent solubility	• literature
Model Parameters		
Transformation coefficient	surface and soil constituent transformation coefficients	• laboratory or field surface retention studies • estimation from literature
Mobility threshold	field mobility threshold	• estimation from field characteristics and chemical constituent properties

5.0 MODELLING TRANSPORT & FATE OF PESTICIDES UNDER TILE DRAINAGE*

5.1 Scenarios and Limitations

The processes of pesticide transmission and transformation within the soil layers are not well understood. Even with a simple modelling approach involving lumped first order processes - the involvement of several zones (surface, upper & lower soil layers) adds to the complexity of the chemical - water interactions. For the following scenarios, the quality submodels have not been calibrated but involve the selection of literature selected values for the parameters. However, the water quantity submodels have been calibrated and verified. As a result of these assumptions the exercise is limited to its value as an index to identify the relative importance of various physical and chemical parameters in the tile drained field "environment".

In the subsequent sections, the following scenarios are investigated.

- **Simulation of Constituent Fate for Two Actual Events**
  Representative metolachlor application loadings were modelled under two actual rainfall events on the Napanee Field. Representative parameter values for this pesticide were selected from the literature. Metolachlor was traced through the surface, and upper and lower soil layers and its fate was summarized.
- **Effect of Rainfall on Pesticide Fate**
  Because pesticide fate depends strongly on rainfall, the effect of simulated metolachlor fate on idealized storms of various intensity and timing was investigated
- **Effect of Chemical Specific Characteristics on Pesticide Fate**
  Because there are a number of pesticides in use the effects of two major parameters, the solubility and the transformation process coefficient, were investigated.

* This section is taken with minor modifications from the M.Sc. thesis by Sharon A. Peters entitled "Development of a Water Quality Submodel for Tile Drained Agricultural Fields".

- **Effect of Field Characteristics on Pesticide Fate**

  After the effect of rainfall and chemical parameters on pesticide fate, the influence of soil types and tile drain characteristics are the most important variables controlling pesticide fate. Soil type and tile drain spacing were the two field characteristics investigated.

5.2 Simulation of Constituent Fate for the Napanee Field

A chemical constituent fate simulation model may be used to obtain information that allows for implementation of agricultural management practices that promote the most efficient and economical use of agricultural chemicals, especially pesticides. For pesticides to be used efficiently, losses to runoff (surface and tile) and losses to reaction or transformation processes must be minimized. Residence time within the upper soil layer must be extended to maximize pesticide availability to plant uptake and pest interception. Runoff losses from agricultural fields must be minimized to reduce the potential environmental impact of pesticides on receiving water bodies.

The water quality version of TILE was used to simulate the fate of a selected chemical constituent, the pesticide metolachlor (active ingredient 2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxy-1-methylethyl) acetamide). Metolachlor is a relatively new herbicide, which was registered for use in Canada in 1978 (Patni *et al.* 1987) and is becoming popular in southern Ontario. It is recommended for use with a variety of crops including corn, soybeans and other beans and potatoes and is effective against a number of grasses and other broadleaved weeds (Ontario Ministry of Agriculture and Food 1988). Table 5.1 details the TILE water quality model input data estimated for simulation of metolachlor fate.

Metolachlor fate was simulated for the two spring rainfall events (starting May 19 and June 11) recorded in 1986 for the Napanee experimental field. These two events were representative of spring conditions likely to be encountered soon after application of pesticide to the field. The Napanee field and soil characteristics employed in these two simulations were those listed in Table 4.5. Initial soil water contents for the upper soil layer were chosen as 0.14

and 0.20 for the May and June events. These values were selected based on the results of calibration exercises performed for the two events. Calibration also indicated that the appropriate initial water content for the lower soil layer for the two events was the field capacity water content, or 0.45.

Table 5.1 TILE water quality model input data for metolachlor fate simulation

INPUT DATA TYPE	CHARACTERISTIC OR PARAMETER	UNITS	VALUE
Scenario Characteristics	initial surface mass	mg/m^2 (5)	0.0
	initial upper layer mass	mg/m^2	0.0
	initial lower layer mass	mg/m^2	0.0
	application mass (1)	mg/m^2	250
	application timing	-	first timestep
	application method	-	surface broadcast
	metolachlor solubility (2)	mg/L	530
Model Parameters	surface transformation coefficient (3)	-	0.005
	soil transformation coefficient (4)	-	0.0005
	field mobility threshold	mm (water)	1.0

(1) Estimated based on Patni *et al.* (1987)
(2) Estimated from United States Environmental Protection Agency Office of Drinking Water Health Advisories (1989)
(3) Estimated from persistence studies reported in United States Environmental Protection Agency Office of Drinking Water Health Advisories (1989)
(4) Estimated from persistence studies reported in United States Environmental Protection Agency Office of Drinking Water Health Advisories (1989)
(5) Units of mg/m^2 refer to mg of chemical constituent per m^2 of field area.

Time series plots of the seven day simulation periods for the two events are presented on Figures 5.1 to 5.3. Figure 5.1 shows rainfall hyetographs and simulated and observed tile flows, along with simulated metolachlor masses lost through tile flow, for the May 19 and June 11, 1986 events. Both events are complex and include rainfall inputs of varying intensities, separated at times by periods without rain. The dependence of the tile flow hydrograph on antecedent soil water contents is clearly illustrated for the May 19, 1986 event, during which the initial rainfall of 18 mm was absorbed into soil water storage without generation of tile flow, as confirmed by the observed tile flow hydrograph recorded for the event. The two components of the tile flow hydrograph (early drain response and later continuous slow release of water from the soil matrix) reported by Whyte (1988) were also present in the two events illustrated on Figure 5.1. The dependence of the simulated mass lost to the field system through tile flow on the volume of tile flow generated is clearly shown by the tile mass transport series' presented.

Figures 5.2 and 5.3 illustrate the changes in metolachlor mass stored in each of the upper and lower soil layers during the simulation period and the corresponding cumulative system losses to transport and transformation processes for the May 19 and June 11, 1986 events respectively.

The early high intensity rainfall (18 mm within the first hour) recorded during the May 19, 1986 event shown on Figure 5.2 resulted in immediate elevation of the surface storage water content above the solubility and field mobility threshold estimated for metolachlor and transfer of the entire applied constituent mass into the upper soil layer during the first hour. As rainfall continued and water percolated from the upper to the lower soil layer, carrying with it metolachlor mass, the storage mass in the upper layer decreased, while that in the lower layer increased. Initially, less mass was lost from the lower layer to the tiles and by transformation than entered the lower layer from the upper, and so the lower layer storage mass increased as the simulation progressed. The plot of cumulative metolachlor mass lost to tile flow (Figure 5.2) shows significant increases corresponding to the early drain response tile flow component observed to follow rainfall inputs. Between rainfall inputs, the cumulative mass lost to tile flow increased more slowly, reflecting the slower release of water from the soil matrix. Later in the simulation period, rainfall has stopped and tile flow generation and metolachlor mass loss through the tiles has correspondingly slowed. The gradual decline in stored mass observed later in the

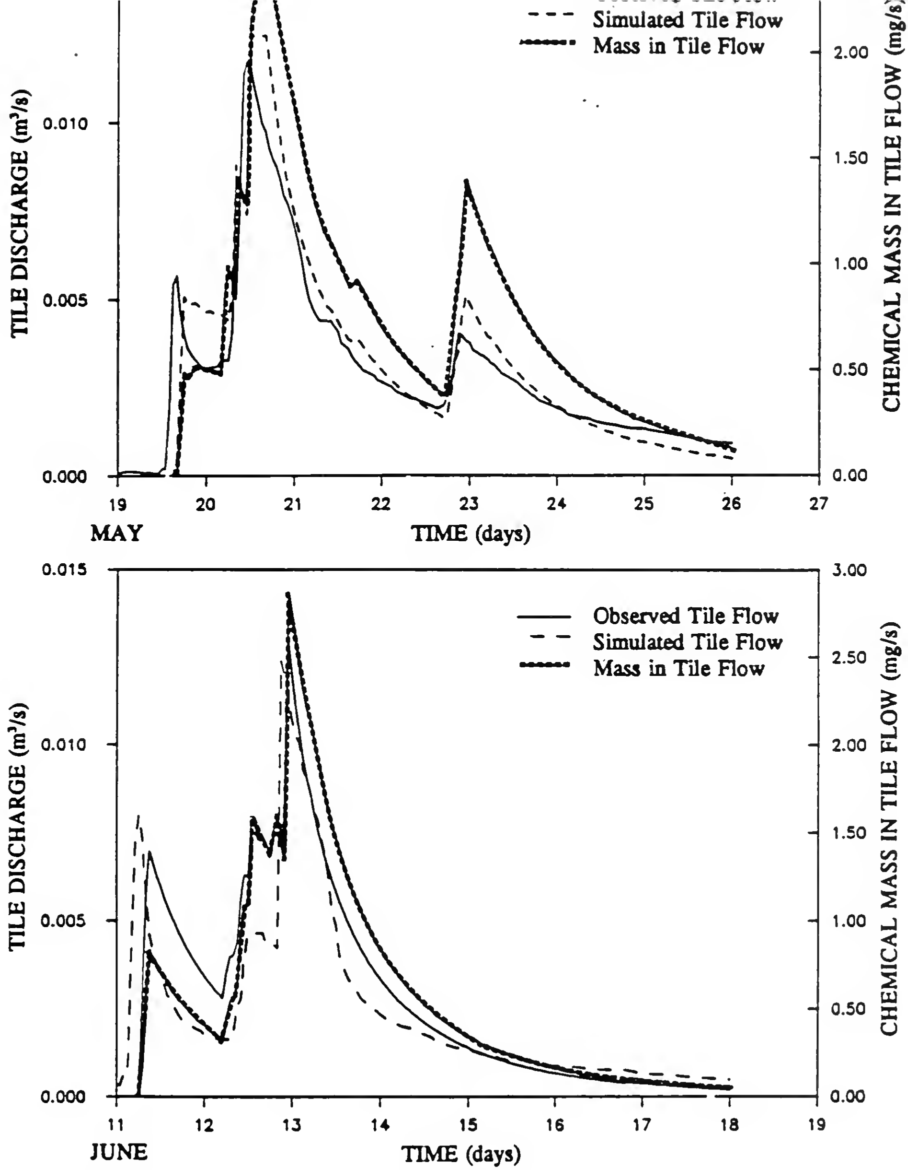


Figure 5.1 Tile flow and associated pesticide mass time series - May 19 and June 11, 1986 events

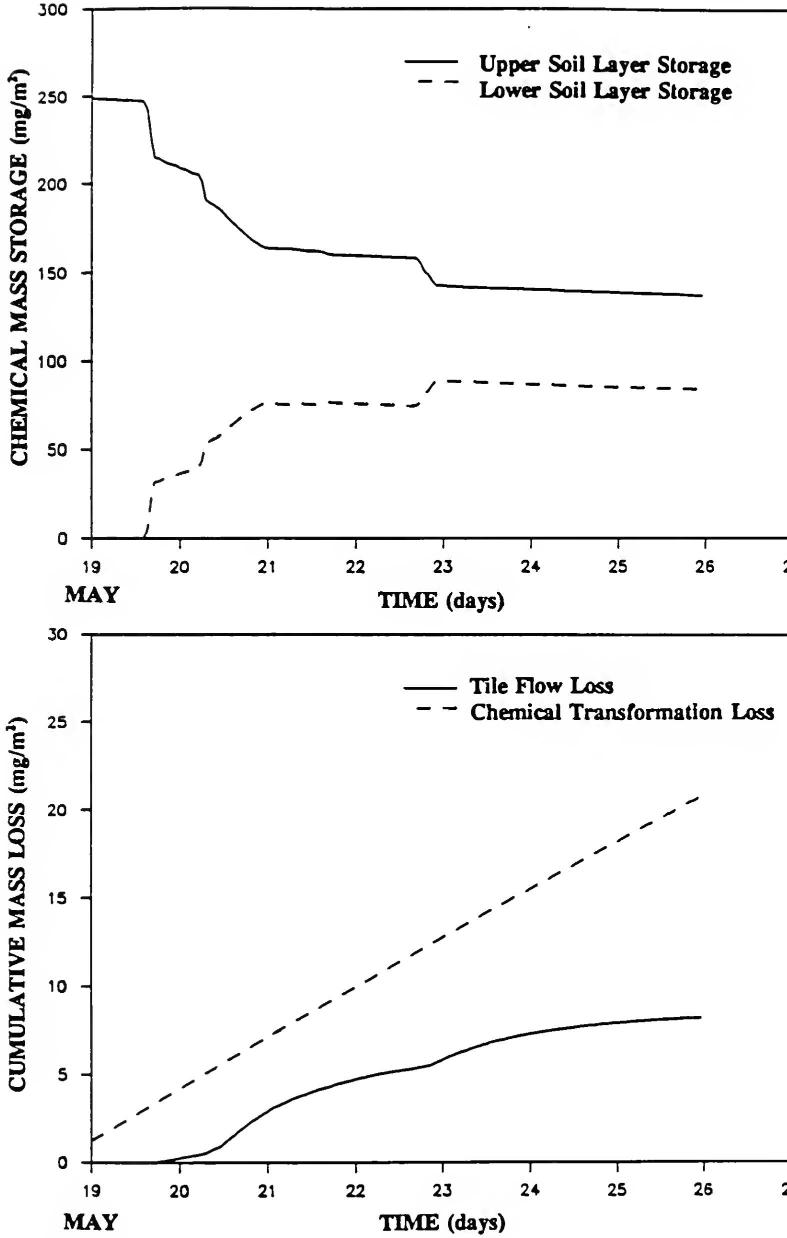


Figure 5.2 Pesticide mass storage time series and cumulative pesticide losses - May 19, 1986 event

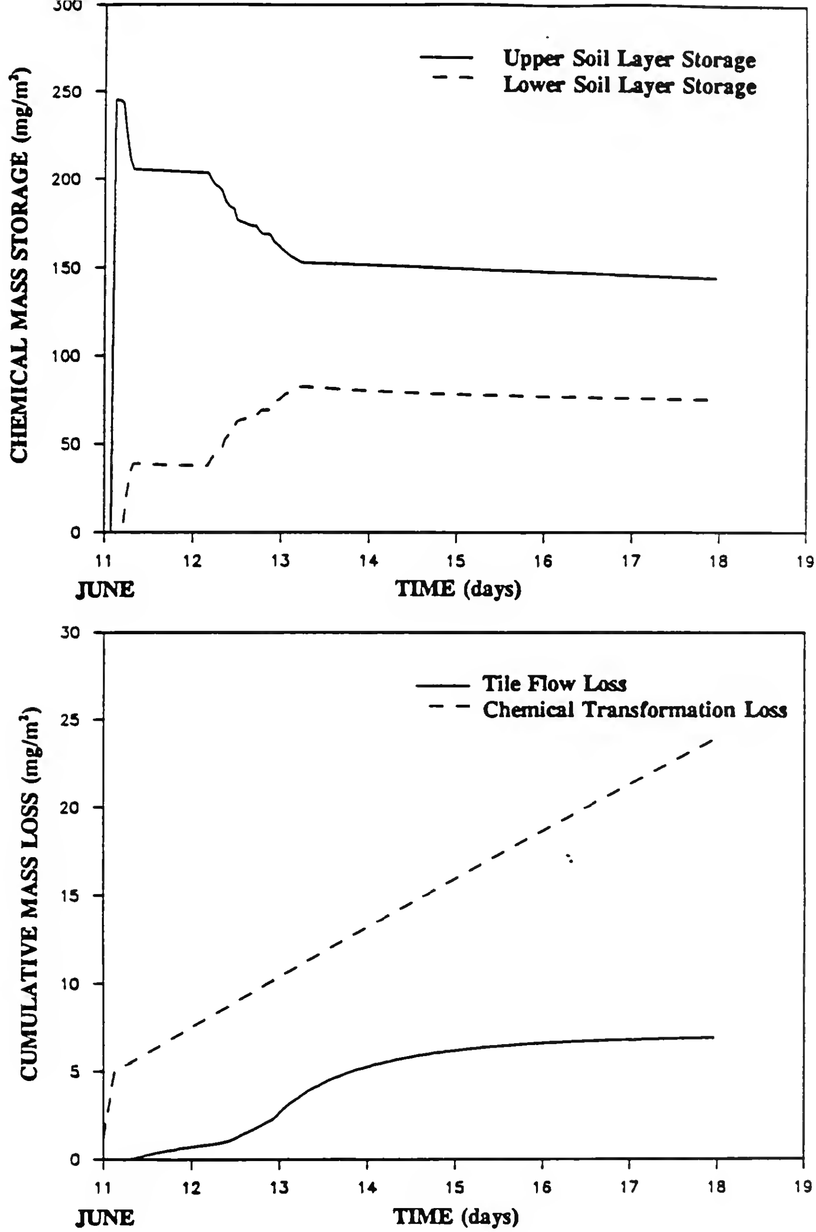


Figure 5.3 Pesticide mass storage time series and cumulative pesticide losses - June 11, 1986 event

simulation period is primarily the result of ongoing metolachlor loss by transformation processes. Due to the transfer of the entire metolachlor mass into the upper soil layer during the first hour of the simulation, the plot of cumulative metolachlor loss to transformation processes shows a linear increase throughout the simulation period, reflecting the operation of the single soil storage transformation coefficient on the mass stored in the field system.

As shown on Figure 5.3, the plots of metolachlor mass stored in the upper and lower soil layers for the June 11, 1986 event are similar to those observed for the May 19, 1986 event. The smaller rainfall volume recorded during the first few hours of the June simulation resulted in a delay in transfer of the metolachlor mass from the depression storage into the upper soil layer compared to the May event. Following transfer of the mass into the upper soil layer, the upper layer storage decreased and lower layer storage increased as percolation carried metolachlor mass into the lower layer and tile flow was generated. Cumulative mass lost to tile flow increased significantly during the early drain response stage of the tile flow hydrograph and levelled off asymptotically during the later slow soil matrix response stage. Cumulative mass lost to transformation processes showed a two part increase during the June event, reflecting the transfer of mass from the surface storage reservoir with its relatively larger transformation process coefficient, to the upper soil layer during the early hours of the simulation.

Table 5.2 summarizes the simulation results for the two events. Surface flow was generated during both events, but due to the timing of the high intensity rainfalls responsible, no associated pesticide losses to surface runoff occured. During each event, the high intensity rainfalls were preceeded by lower intensity rains of sufficient volume to transfer metolachlor masses applied to the field by the surface broadcast method to the upper layer soil storage reservoir. The metolachlor was thus unavailable to transport by surface flow. As a result, simulation responses for the two pesticide application methods were found to be similar to each other for the two events presented.

Table 5.2 Summary of metolachlor fate simulation results

MODEL OUTPUT	UNITS	MAY 19, 1986 EVENT	JUNE 11, 1986 EVENT
Water Quantity Results			
Length of simulation	h	168	168
Total rainfall	mm/m^2 *	91.8	71.4
Simulated surface runoff	mm/m^2	13.6	12.2
Simulated tile flow	mm/m^2	38.1	34.0
Observed tile flow	mm/m^2	36.2	29.6
Simulated peak tile discharge	m^3/s	0.0125	0.0129
Observed peak tile discharge	m^3/s	0.0117	0.0124
Metolachlor Fate Results			
Total mass applied to field	mg/m^2 ** (% of applied mass)	250 (100)	250 (100)
Total mass lost in surface flow	mg/m^2 (% of applied mass)	0 (0)	0 (0)
Total mass lost in tile flow	mg/m^2 (% of applied mass)	8.2 (3.3)	6.9 (2.8)
Total mass lost to transformation processes	mg/m^2 (% of applied mass)	20.8 (8.3)	23.9 (9.6)
Mass remaining in surface storage	mg/m^2 (% of applied mass)	0 (0)	0 (0)
Mass remaining in upper layer storage	mg/m^2 (% of applied mass)	137 (54.8)	144 (57.6)
Mass remaining in lower layer storage	mg/m^2 (% of applied mass)	83.9 (33.6)	75 (30.0)

* water volumes are expressed as depths in mm distributed across the area of the field

** constituent masses are expressed in mg per m^2 of field area

5.3 Effect of Rainfall on Pesticide Fate

In response to the strong dependence of modelled pesticide fate on surface and tile flow hydrographs, which in turn depend on rainfall characteristics, demonstrated by the event simulations described above, the effects of rainfall characteristics on simulated pesticide fate were investigated. Idealized storms, corresponding to specific return periods tabulated by the Atmospheric Environment Service (AES) for the Kingston Pumping Station, were used to provide a common basis for comparison of the effects of two characteristics: rainfall intensity and rainfall timing.

5.3.1 Rainfall Intensity

To investigate the effects of rainfall intensity on metolachlor fate, the idealized six-hour storms listed in Table 5.3 were simulated over an arbitrary ten day period. Field and soil characteristics corresponding to the Napanee field were employed and initial soil water contents were selected at field capacities for both soil layers for comparison purposes. Chemical constituent characteristics corresponding to those selected for metolachlor, as described in Table 6.1 above, were used and each rainfall scenario was simulated for both surface broadcast and incorporation application methods.

Figure 5.4 illustrates the simulated pesticide runoff losses due to both surface and tile flow for the two application methods investigated. The pesticide losses are presented as percentages of the applied pesticide mass. As rainfall intensity increased, pesticide losses increased dramatically for the surface application scenarios because the pesticide was available to transport by surface flow and subsequent loss to the field system. Simulated losses to surface flow ranged from 0 (storms with return periods ≤ 2) to 50 (100-year storm) percent of the applied pesticide mass for the surface application method. Tile losses associated with surface application of the pesticide ranged from 0.8 to 1.6 percent of the applied mass and transformation losses ranged from 9.1 to 15 percent.

Table 5.3 Idealized six hour storms

RAINFALL DEPTH (mm)	RAINFALL INTENSITY (mm/h)	RETURN PERIOD (years) *
24.0	4.0	<2
36.0	6.0	2
49.0	8.2	5
56.0	9.6	10
68.5	11.4	25
84.6	14.1	100
* Return periods presented are based on Atmospheric Environment Service (AES) data tabulated for Kingston Pumping Station.		

For the incorporation scenarios, however, runoff losses were largely independent of rainfall intensity (ranging from 1.5 to 1.7 percent of the applied mass) since they were limited to losses associated with generation of equilibrium tile flow. Transformation losses for the incorporation applications were consistent at 12 percent of the applied mass for all rainfall intensities investigated.

At rainfall intensities less than those necessary for generation of surface flow, which corresponded to a return period of approximately two years for the scenarios investigated, runoff losses were made up entirely of tile flow losses and were independent of pesticide application method.

Figure 5.5 illustrates the percentages of applied mass which were retained in the upper and lower soil storage reservoirs at the end of the ten day simulation period for each of the rainfall intensities and the two pesticide application methods investigated. The majority of the stored pesticide was retained in the upper layer for all cases investigated. As shown in Figure

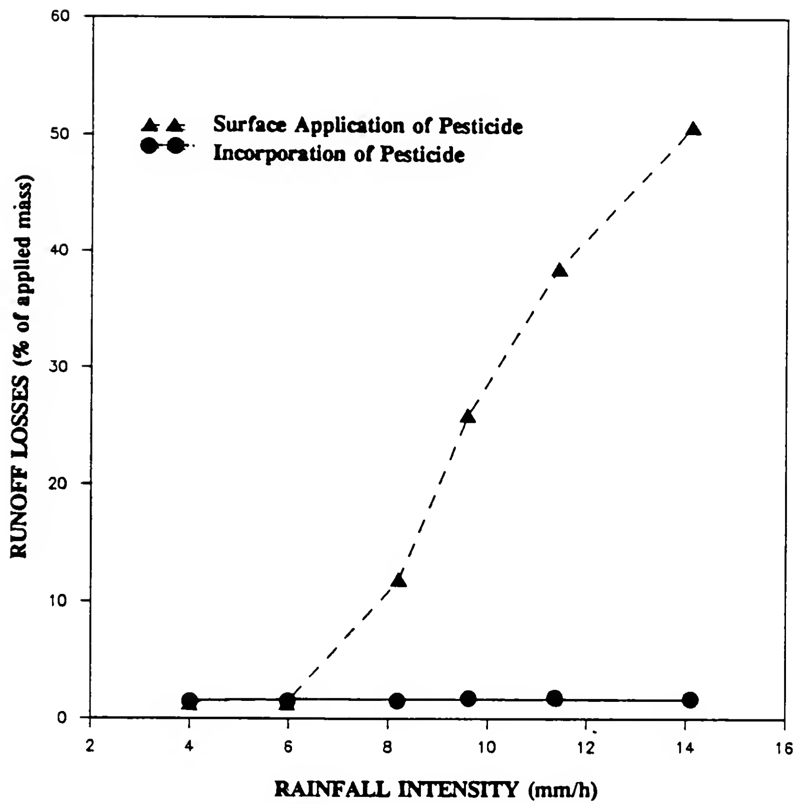


Figure 5.4 Effect of rainfall intensity on surface and tile runoff losses

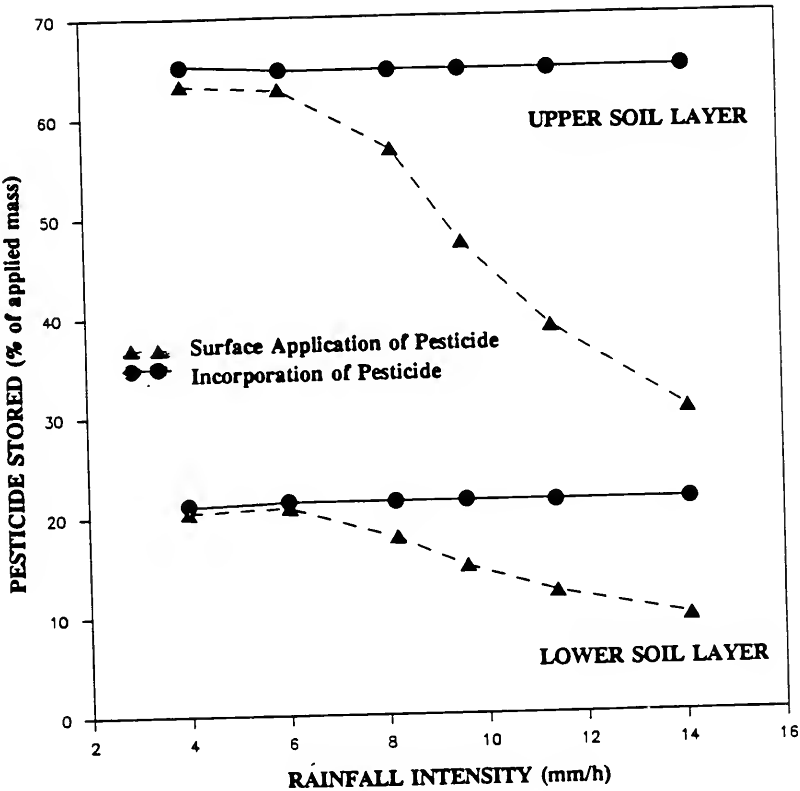


Figure 5.5 Effect of rainfall intensity on pesticide mass

5.5, however, stored masses in both the upper and lower layers decreased with increasing rainfall intensity for the surface application scenarios due to the associated increase in pesticide loss to surface flow. The mass retained was largely independent of rainfall intensity for the incorporation method.

5.3.2 Rainfall Timing

To investigate the effects of rainfall timing on simulated metolachlor fate, two of the idealized six hour storms were applied to the Napanee field for a range of time intervals between pesticide application and rainfall. Two factors were expected to affect the results produced. The first was the variation in the length of time the pesticide was present on the field and subject to transformation processes before the advent of the rainfall. The second and less significant factor was the variation in initial soil water contents arising from the length of time evapotranspiration acted to remove water from the soil storage system before the advent of the rainfall.

The two six hour storms chosen were the 4 mm/h rainfall (return period < 2 years) which did not result in generation of surface flow during the investigation of the effects of rainfall intensity on simulated pesticide fate and the 9.6 mm/h rainfall (10 year return period) which did result in generation of surface flow for the field characteristics and antecedent soil water contents specified. The effect of rainfall timing was investigated for both surface broadcast and incorporation application methods.

Figure 5.6 illustrates the effect of rainfall timing on cumulative losses to transformation processes recorded at the end of the simulation period for the two rainfall events selected and the two pesticide application methods investigated. Simulated transformation losses increased with increasing time interval between field application and the advent of rainfall for both application methods. Transformation losses were also significantly dependent on application method for rainfall intensities capable of surface flow generation. The responses reported for the two simulations involving surface pesticide application were almost identical to each other, as were those reported for the two rainfall scenarios where the pesticide was incorporated in the upper soil layer. The differences between the transformation losses reported for simulations

involving the two application methods are largely due to the order of magnitude difference assigned to the surface and soil transformation process coefficients. Surface broadcast applications resulted in longer constituent residence times in the surface storage reservoir and correspondingly larger transformation losses due to processes modelled with the larger coefficient.

Figure 5.7 illustrates the variation in runoff losses as a result of rainfall timing for the two rainfall events and two pesticide application methods investigated. The greatest runoff losses (up to 26 % of the applied mass when rainfall occurred directly following pesticide application) resulted from surface runoff losses produced by the combination of the ten year return period rainfall applied to the field with the pesticide applied by surface broadcast. Runoff losses generally tended to decrease slightly with increasing interval between time of application and onset of rainfall as a result of the increase in transformation process losses reported. As transformation losses increased, less mass was available for transport by surface and tile runoff waters.

It is interesting to note that no runoff losses were reported for the 20 day interval between pesticide application and rainfall, low rainfall intensity simulations for both application methods. During the 20 day interval, simulated evapotranspiration significantly reduced the soil water contents in the upper and lower soil layers so that the 24 mm of rain which fell on the field during <2 year return period storm was used to satisfy the soil water deficit created and no tile flow was generated.

Figure 5.8 shows the effect of rainfall timing on the constituent mass stored in the upper soil layer at the end of the simulation period. Both simulation scenarios involving surface application of the pesticide resulted in a sharp decrease in the mass percentage stored in the upper layer with increasing time between application and rainfall. This decrease reflects the increasing percentage of pesticide mass lost to transformation processes. The difference between the storage values corresponding to no delay between pesticide application and rainfall for the two rainfall intensities is a result of the mass lost to the surface runoff generated by the 10 year storm.

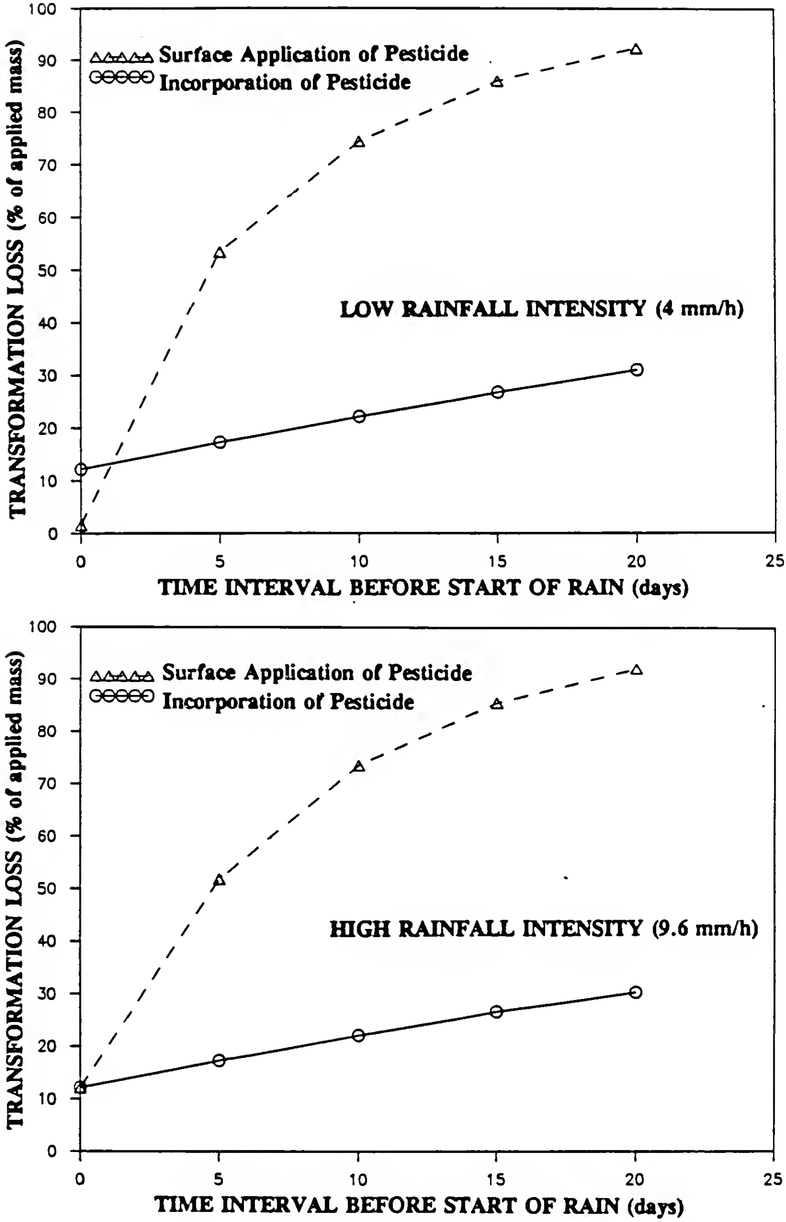
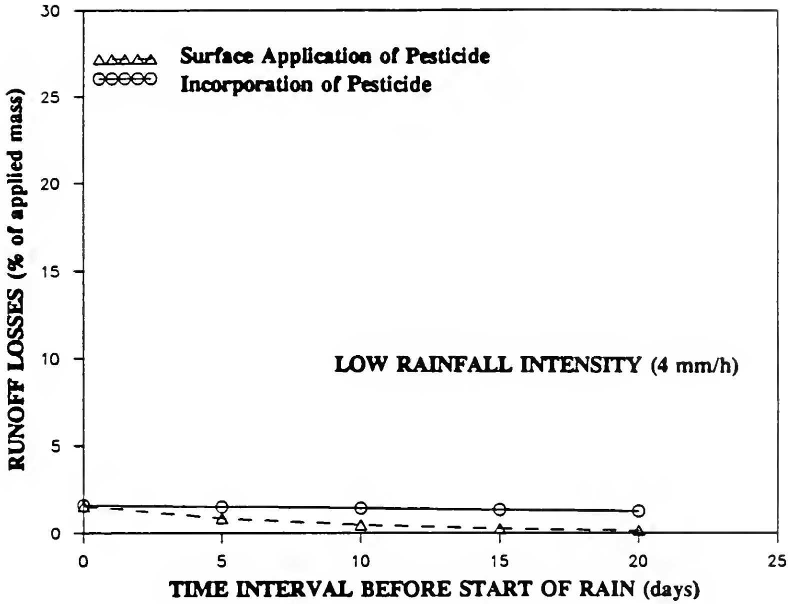


Figure 5.6 Effect of rainfall timing on pesticide losses



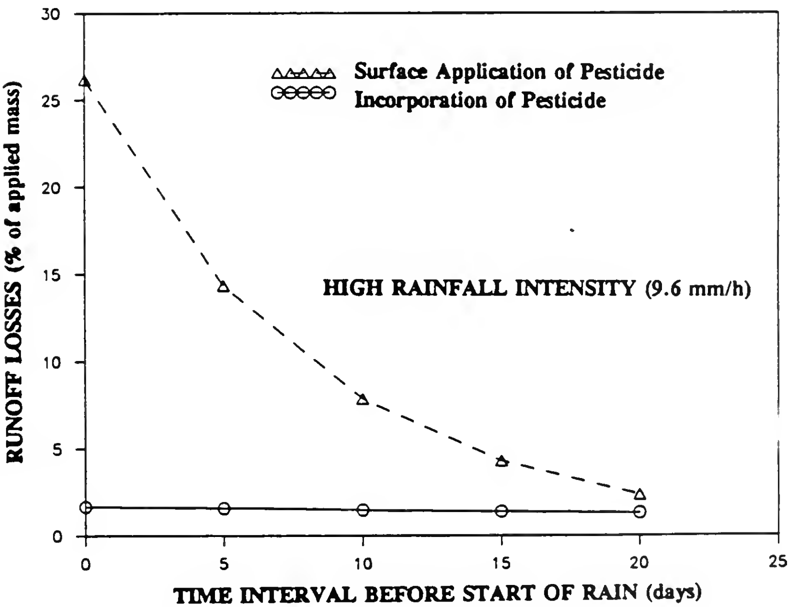


Figure 5.7 Effect of rainfall timing on surface and tile runoff pesticide losses

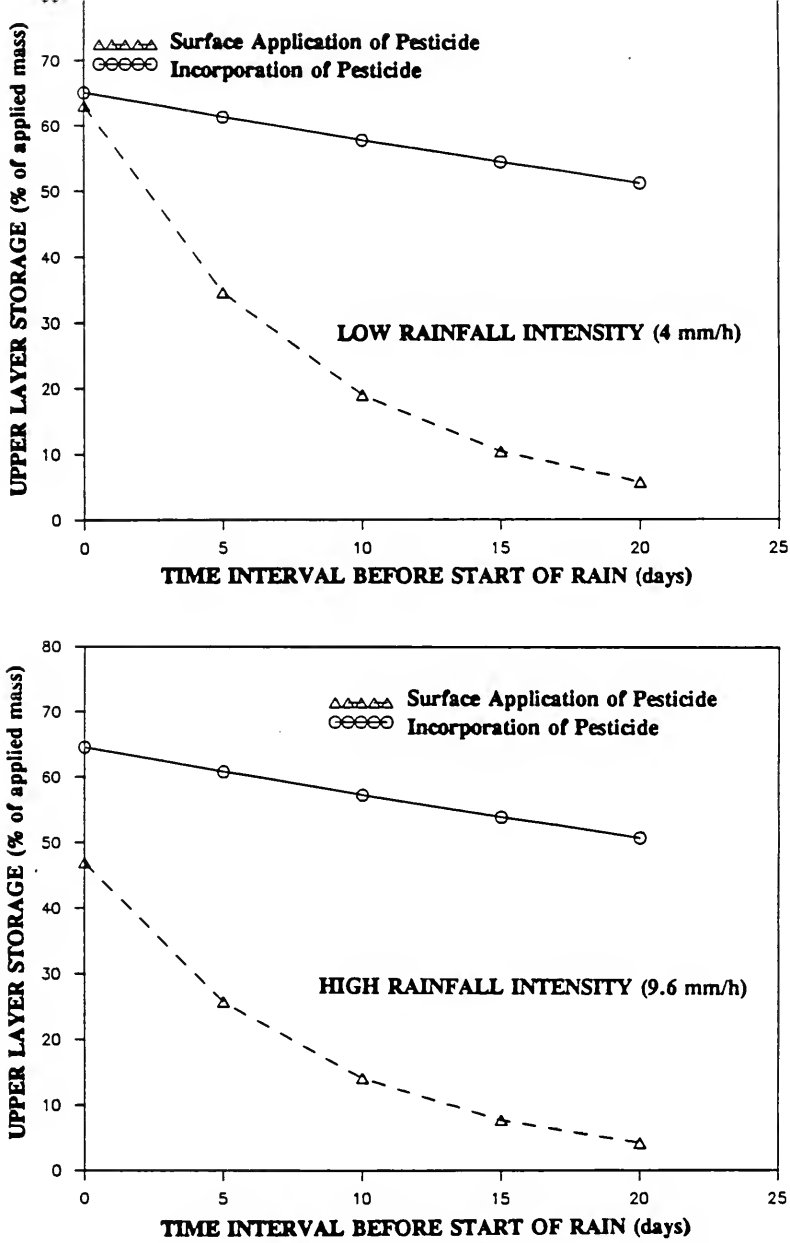


Figure 5.8 Effect of rainfall timing on pesticide stored in upper soil layer

The 10 year rainfall scenario for the incorporation application case produced a curve similar in shape to those observed for the two surface application cases. The reduction in upper layer storage with increasing time interval between application and rainfall was less severe for the incorporation simulation because of the lower transformation process coefficient specified for the soil storage layers. The results for the <2 year storm with incorporated pesticide were distorted by the proximity of the rainfall applied to the soil water content required by the field mobility threshold specified for metolachlor transport on the Napanee field. For the scenarios featuring longer time intervals between pesticide application and rainfall and correspondingly larger evapotranspiration soil water losses, addition of the low intensity rainfall did not result in the presence of sufficient water for pesticide mobilization to occur. This resulted in a delay in mobilization, which is reflected in the slight rise in the percentage of mass stored in the upper layer at the end of the simulation period. During the 20 day interval simulation, in which no tile flow was generated, the low soil water content in the upper soil layer did not allow for the transfer of any pesticide mass to the upper layer and thus resulted in a storage mass of zero at the end of the simulation.

5.4 Effect of Chemical Specific Characteristics on Pesticide Fate

In the absence of a comprehensive data set suitable for calibration of the TILE model constituent fate algorithms, model response to constituent properties, which were estimated from the literature, was investigated. The two chemical constituent specific characteristics included in the fate simulation model are the solubility the estimated lumped transformation process coefficient. The simulations performed to investigate model response to variation in rainfall and field characteristics employed chemical constituent characteristics selected to represent the pesticide metolachlor. It is recognized, however, that agricultural chemicals exhibit a wide variety of chemical properties and that a model which attempts to simulate the fates of different chemicals must allow for realistic consideration of the expected variation in chemical properties.

5.4.1 Chemical Solubility

To investigate the effect of variation in chemical solubility on simulated fate, five

pesticides with solubilities ranging over four orders of magnitude were selected. The selected pesticides and their solubilities in water, as reported in the literature, are presented in Table 5.4. Review of pesticide persistence studies indicated that the application rate of 250 mg/m^2 utilized for metolachlor provided a reasonable basis for comparison of the behaviour of different pesticides.

Table 5.4 Selected pesticides and their solubilities in water

PESTICIDE	SOLUBILITY IN WATER (mg/L)
metolachlor	530
cyanazine	171
atrazine	30
toxaphene	0.4
trifluralin	0.05

(after Buttle 1989, Pierce and Wong 1988, Weber *et al.* 1980 and Willis and McDowell 1982)

Simulations were performed for each pesticide using the May 19 and June 11, 1986 events, Napanee field characteristics, a constant application rate of 250 mg/m^2 and both surface broadcast and incorporation application methods. Each of the events utilized was an actual recorded precipitation event consisting of a series of rainfall inputs to the field occurring over a number of timesteps.

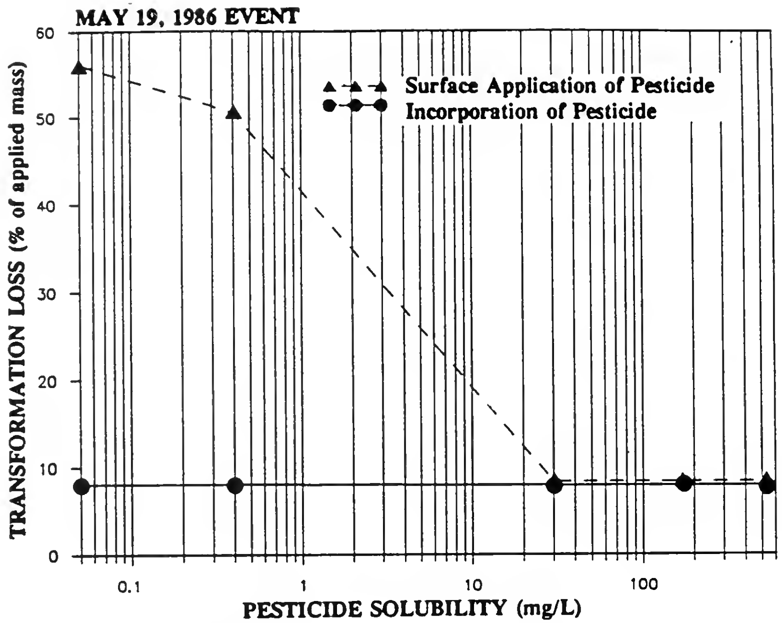
Figures 5.9 and 5.10 illustrate the effect of constituent solubility on the cumulative pesticide losses to transformation processes and runoff respectively reported for the May 19 and June 11, 1986 event simulations. As shown on Figure 5.9, losses to transformation processes for the two events were essentially consistent at approximately ten percent of the applied mass, with the exception of the scenarios involving surface application of pesticides with low solubilities.

Significant masses of the low solubility pesticides were retained in the surface storage reservoir throughout the simulation period. Rainfall inputs to the field during later stages of the simulations resulted in ongoing solution and transport of pesticide mass from the surface storage reservoir. Pesticide mass mobilized in the later stages of the simulation was then available to transformation processes higher transformation losses of between 50 and 60 percent of the applied pesticide mass were incurred.

With the exception of the scenario combining the June 11 event with surface broadcast application, simulated pesticide runoff losses were largely independent of solubility for solubilities larger than approximately 10 mg/L. Pesticide losses to surface runoff were incurred midway through the simulation period for the May 19 events with toxaphene and trifluralin applications (solubilities 0.4 and 0.05 mg/L) and for the June 11 event with atrazine (solubility 30 mg/L), toxaphene and trifluralin applications. Surface broadcast applications scenarios involving pesticides with higher solubilities (metolachlor and cyanazine) led to complete constituent mobilization and transfer into the soil layer before generation of surface flow. Lower pesticide solubilities resulted in retention of part of the applied mass in the surface storage reservoir where it was available for transport out of the field system by surface flow.

Of the scenarios involving surface runoff losses, only the June 11 event simulated with atrazine resulted in availability and transport by surface flow of a significant pesticide mass, as shown on Figure 5.10. Pesticides with extremely low solubilities were associated with very low runoff losses since only small quantities of these constituents were mobilized and transported during the simulation periods.

Figure 5.11 illustrates the effect of pesticide solubility on the percentage of the applied mass retained in the upper soil layer storage reservoir at the end of the simulation period for the two events and the two application methods considered. As for runoff and transformation process losses, the masses retained were found to be largely independent of pesticide solubility for solubilities larger than approximately 10 mg/L. For all simulations involving atrazine, cyanazine and metolachlor, between 50 and 60 percent of the applied mass was retained in the upper soil layer at the end of the simulation period.



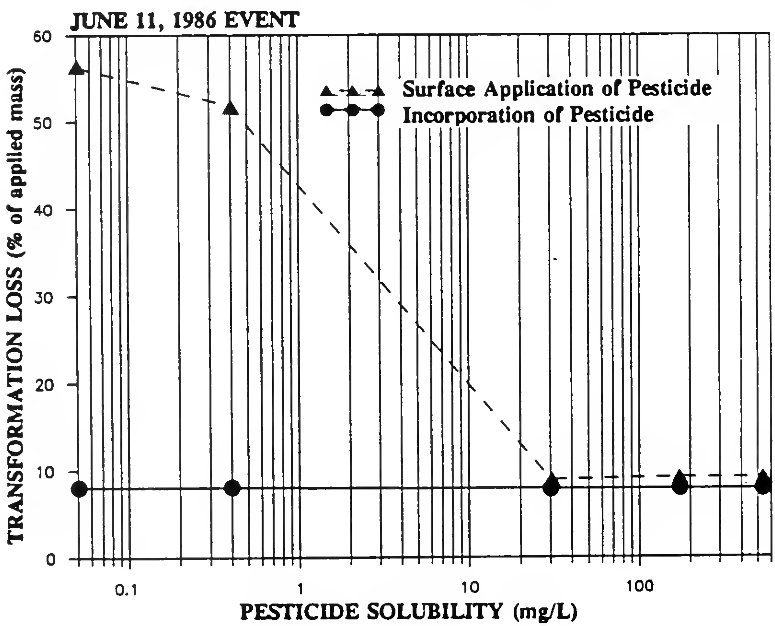


Figure 5.9 Effect of pesticide solubility on transformation process losses

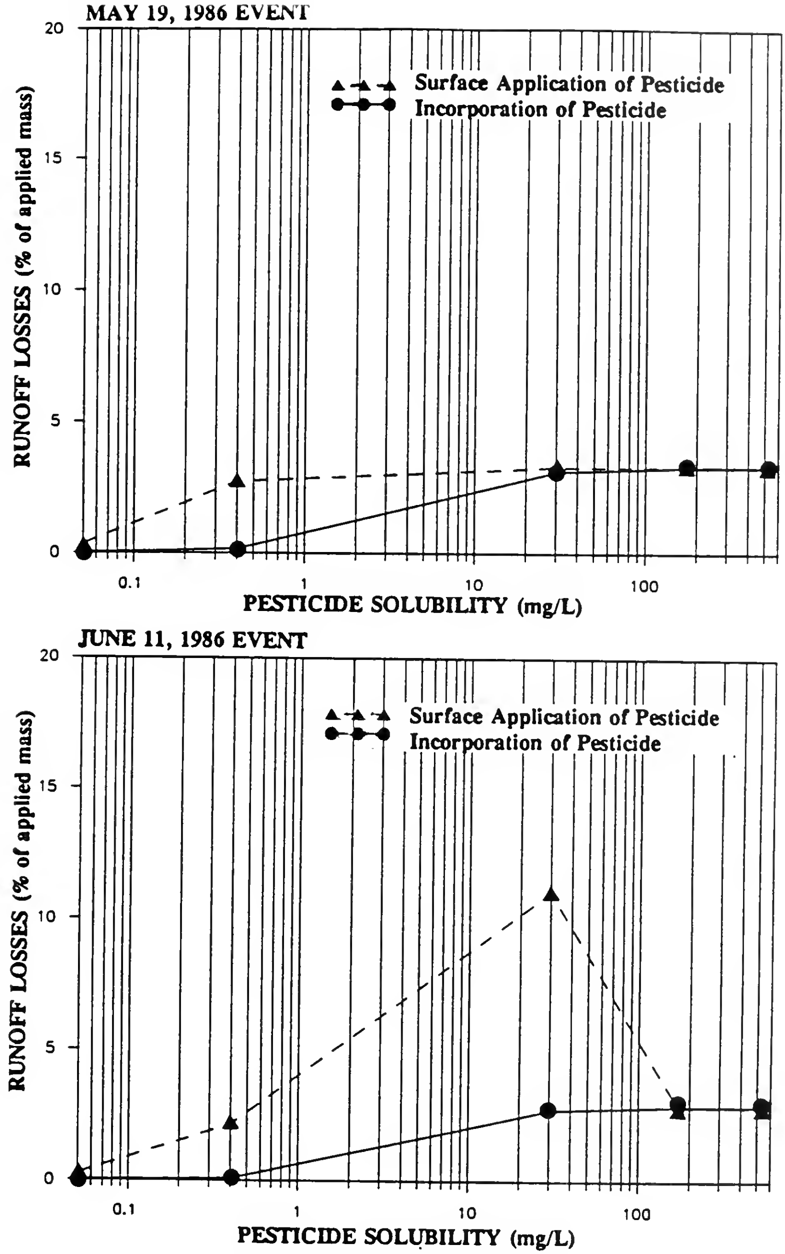


Figure 5.10 Effect of pesticide solubility on runoff losses

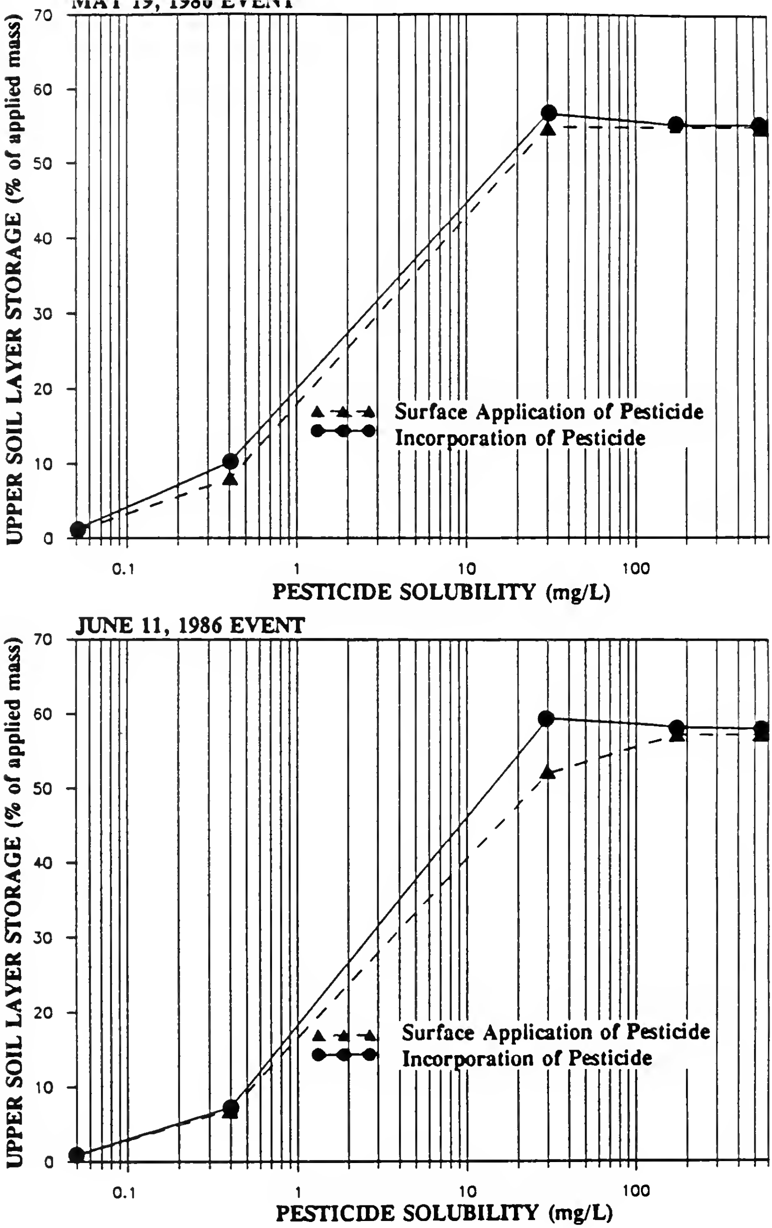


Figure 5.11 Effect of solubility on pesticide mass stored in upper soil layer

In contrast, as shown in Figure 5.11, the simulations involving toxaphene and trifluralin resulted in retention in the upper soil layer of less than ten percent of the mass applied. Low pesticide mass stored in the soil was associated with the low solubility pesticides due to the limited masses of these chemicals dissolved and mobilized during the simulations.

5.4.2 Transformation Process Coefficient

The transformation process coefficients allow for lumped modelling of a number of processes which act to remove chemical constituent mass from transportation pathways. In the absence of field studies quantifying the effects of specific processes, coefficients were estimated from literature values for pesticide half-lives.

The scenarios involved in simulation of metolachlor fate under Napanee field conditions and investigation of the effects of rainfall and field characteristics on metolachlor fate employed transformation process coefficients for soil and surface storage reservoirs which were inferred from published literature values for metolachlor half-lives in soil and exposed to sunlight at the soil surface respectively. To investigate the effects of variation in the selected transformation process coefficient on simulated constituent fate, coefficients derived from reported half-lives for three additional pesticides (atrazine, cyanazine and trifluralin) were selected. Table 5.5 lists transformation process coefficient and half-life ranges for the four pesticides considered. Five coefficients considered representative of these ranges were used in simulation. They were 0.005, 0.002, 0.001, 0.0005 and 0.0003 and corresponded to pesticide half lives of 6, 14, 30, 60 and 100 days respectively.

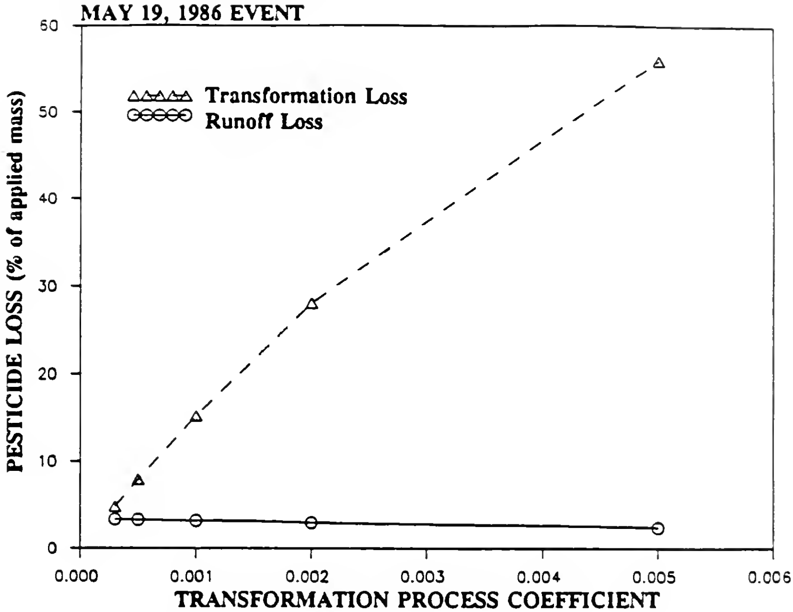
Table 5.5 Half-lives and estimated transformation process coefficients for selected pesticides

PESTICIDE	LITERATURE HALF-LIFE RANGE (days) (t)	TRANSFORMATION PROCESS COEFFICIENT RANGE (k_{tp})
metolachlor	6 - 64	0.0005 - 0.005
cyanazine	14 - 70	0.0004 - 0.002
atrazine	56 - 107	0.0003 - 0.0005
trifluralin	42 - 84	0.0004 - 0.0008
Transformation process coefficients were calculated from pesticide half-lives reported in the literature using $k_{tp} = 1 - \left(\frac{1}{2}\right)^{1/24\,t}$		

(after United States Environmental Protection Agency Office of Drinking Water Health Advisories 1989)

To simplify investigation of the effect of the selected coefficient, the incorporation application method was used in all simulations. With this method the constituent is applied directly into the upper soil layer and bypasses the surface storage reservoir. Thus, only one transformation coefficient, that estimated to represent significant processes acting within the soil column, is applied to the constituent mass during the simulation period. The May 19 and June 11, 1986 events were employed with Napanee field conditions and an application rate of 250 mg/m^2 for simulation of pesticide fates with the various transformation process coefficients.

Figure 5.12 presents the pesticide transformation and runoff losses for simulation of the two events using the incorporation application method. Transformation losses for the two events



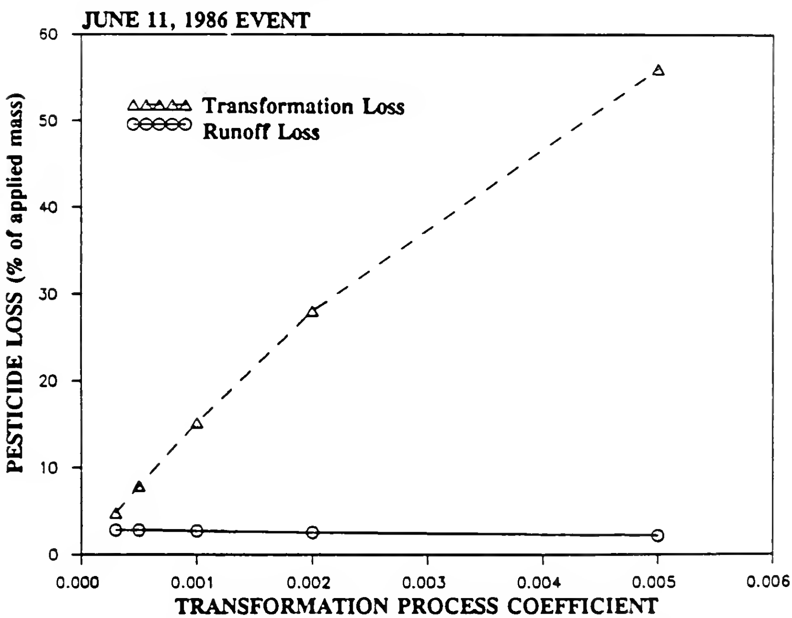


Figure 5.12 Effect of transformation process coefficient on pesticide transformation and runoff losses

were almost identical and ranged from 4.8 percent of applied mass for a coefficient of 0.0003 corresponding to a half-life of approximately 100 days to 56 percent for a coefficient of 0.005 corresponding to a half-life of approximately 6 days. Runoff losses consisted entirely of tile flow losses and were consistent for all simulations investigated at between two and four percent of the applied mass. Thus, for low transformation process coefficients, runoff losses accounted for more than half of all losses, while as the coefficient increased, losses to transformation processes became more significant.

Figure 5.13 illustrates the corresponding mass storages for the upper and lower soil storage layers. Reported upper layer storages ranged between 26 percent (May 19 event, coefficient of 0.005 corresponding to a half-life of approximately 6 days) and 61 percent (June 11 event, coefficient of 0.0003 corresponding to a half-life of approximately 100 days) of the applied mass. Lower soil layer storages ranged from 14 percent (June 11 event, coefficient of 0.005) to 35 percent (May 19 event, coefficient of 0.0005) of the applied pesticide mass.

5.5 Effect of Field Characteristics on Pesticide Fate

In addition to rainfall characteristics, the generated surface and tile flow hydrographs and associated chemical constituent mass transport simulated by the TILE model depend strongly on field characteristics. Paine and Watt (1988) demonstrated that the most significant parameters in calibration of the TILE water quantity model with actual recorded events were the soil hydraulic conductivity, drainable porosity and antecedent soil water contents. In addition, Paine and Watt (1988) used the TILE model to simulate both tiled and untiled field scenarios by varying the spacing between tile drains in order to investigate the benefits of tile installation for a variety of soil conditions. Tile and surface flow response and soil moisture storage were found to be significantly affected by tile drain spacing.

To investigate the effects on simulated pesticide fate of variation in soil hydraulic conductivity and drainable porosity and tile drain spacing, the May 19 and June 11, 1986 events were applied to idealized fields for two sets of soil conditions and three tile drain spacings.

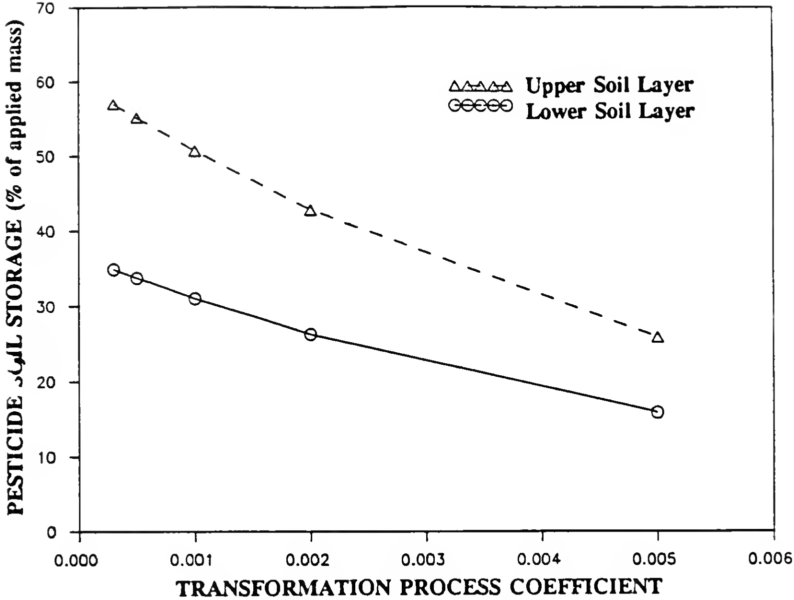
Paine and Watt (1988) presented TILE model calibration results for two southeastern Ontario agricultural fields. The first of these was the Napanee field utilized for the majority of the pesticide fate simulations described above. The second, known as the Leclerc field, is located near Ottawa, as shown on Figure 5.14. Soil characteristics and tile drain spacing from the Leclerc field were used to generate simulations for comparison with those generated for the Napanee field.

5.5.1 Soil Properties

To investigate the effects of soil hydraulic conductivity and drainable porosity on chemical constituent fate, the May 19 and June 11, 1986 events were simulated using Napanee field characteristics and soil properties representative of the Napanee and Leclerc fields, as listed in Table 5.6. Water quantity simulation results were as given in Table 5.2 and metolachlor fate results as affected by the soil characteristics are summarized in Table 5.7.

The tile flow mass hydrographs for the two events and two sets of field conditions are illustrated in Figure 5.13. The simulations for the sandy loam soil of the Leclerc field, with its higher hydraulic conductivity and drainable porosity and lower field capacity soil water contents produced larger volumes of tile flow and correspondingly larger associated pesticide tile runoff pesticide losses. Although surface broadcast pesticide application was employed in the simulations, no surface runoff losses were generated for either of the two events investigated. Transformation losses were found to be consistent for the two sets of field conditions investigated.

Figure 5.16 illustrates the upper and lower soil layer pesticide mass storages simulated for the two sets of field conditions for the two events. Constituent storage in the upper layer was reduced for the Leclerc field soil conditions as compared to Napanee soil conditions, but storage



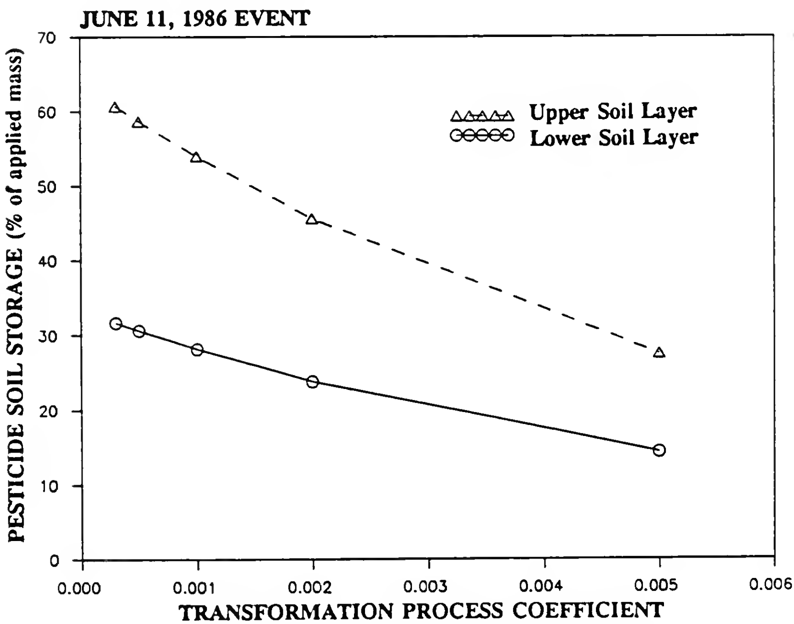


Figure 5.13 Effect of transformation process coefficient on pesticide mass stored in upper and lower soil layers

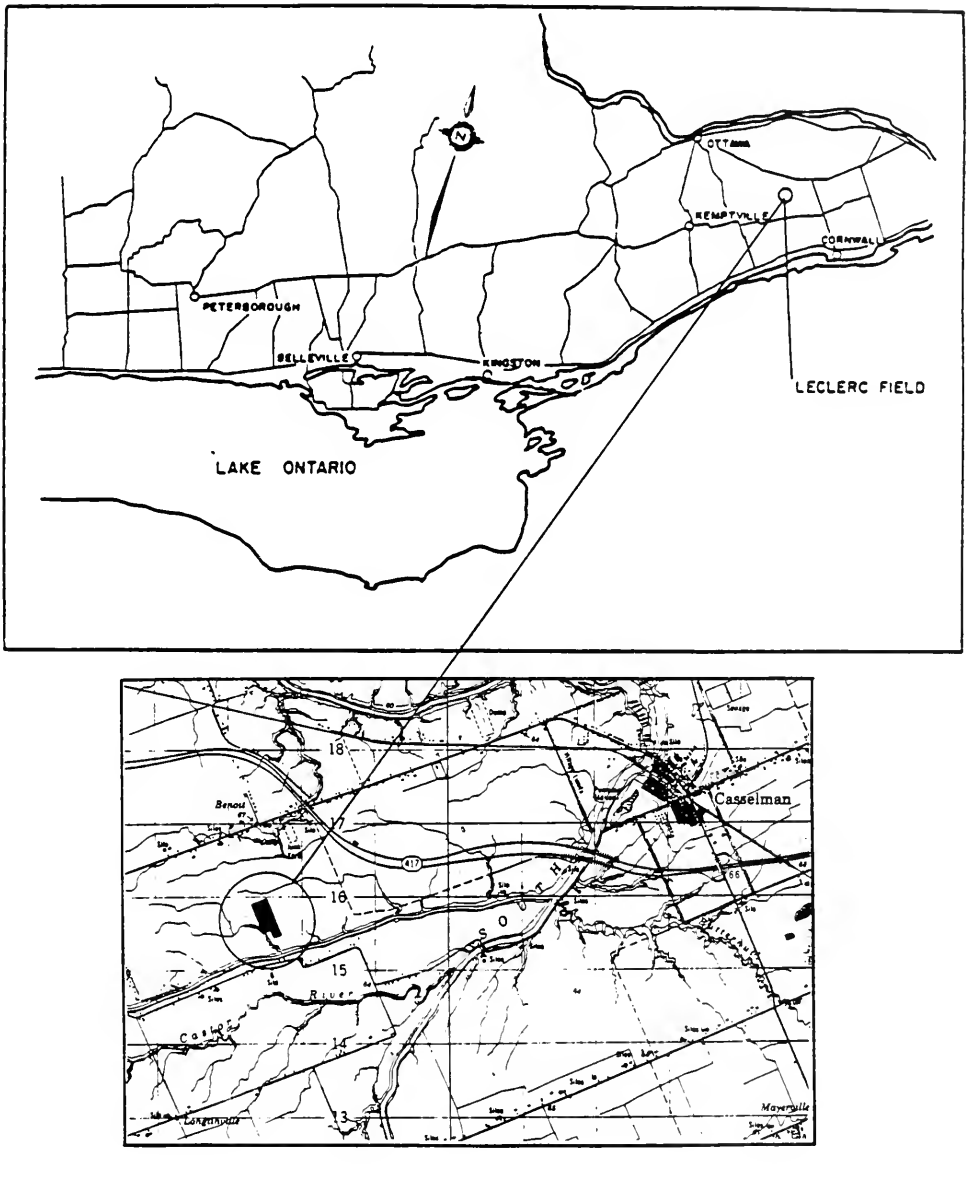
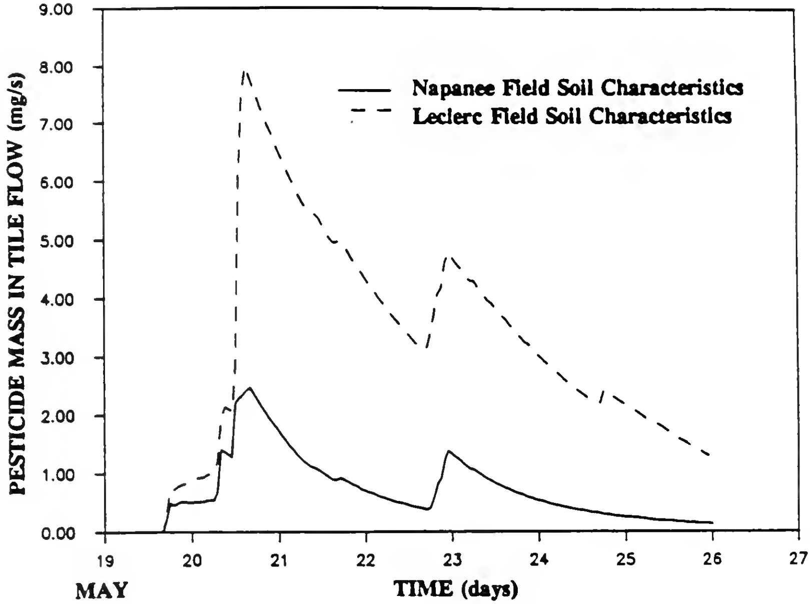


Figure 5.14 Location Plan of Leclerc field (after Paine and Watt 1988)



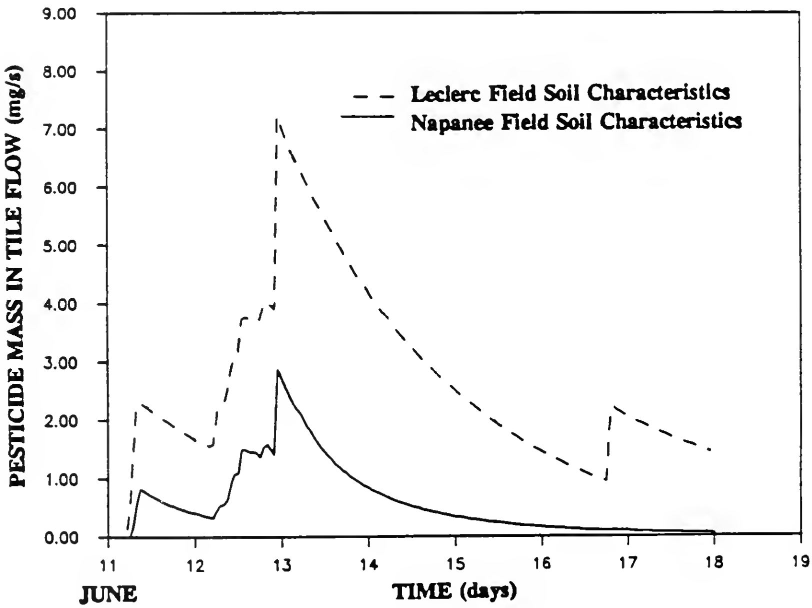


Figure 5.15 Comparison of tile runoff pesticide losses for Napanee and Leclerc field soil characteristics

in the lower layer was increased. Increased lower layer storage and tile runoff pesticide losses for the Leclerc soil conditions were caused by the faster constituent travel time through the soil due to the increased permeability of the Leclerc soil. Loadings to receiving water bodies would thus be increased and efficiency in pest control would be decreased in conjunction with the reduced soil residence time in the upper layer.

Table 5.6 Comparison of Napanee and Leclerc field soil characteristics

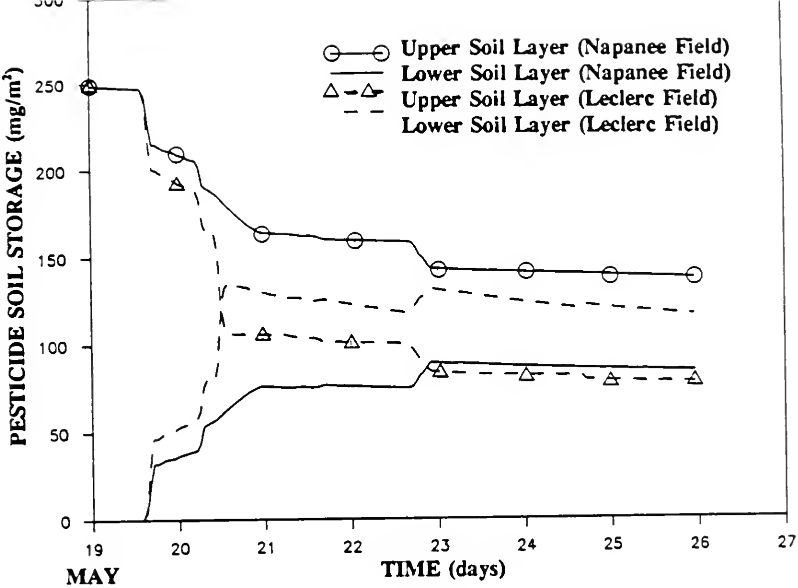
Parameter	Napanee	Leclerc
Hydraulic conductivity	0.38 - 0.40	1.0
Drainable porosity	0.02	0.1
Field capacity (upper layer)	0.25	0.17
Field capacity (lower layer)	0.45	0.17

(after Paine and Watt 1988)

Table 5.7 Summary of metolachlor fate simulation results - effect of soil characteristics

METOLACHLOR FATE RESULTS	UNITS	MAY 19, 1986 EVENT		JUNE 11, 1986 EVENT	
		Napanee	Leclerc	Napanee	Leclerc
Total mass applied to field	mg/m^2 *	250 (100)	250 (100)	250 (100)	250 (100)
Total mass lost in surface flow	mg/m^2	0 (0)	0 (0)	0 (0)	0 (0)
Total mass lost in tile flow	mg/m^2	8.2 (3.3)	36.8 (14.7)	6.9 (2.8)	31.6 (12.6)
Total mass lost to transformation processes	mg/m^2	20.8 (8.3)	19.7 (7.9)	23.9 (9.6)	21.8 (8.7)
Mass remaining in surface storage	mg/m^2	0 (0)	0 (0)	0 (0)	0 (0)
Mass remaining in upper layer storage	mg/m^2	137 (54.8)	77.4 (31.0)	144 (57.6)	80.7 (32.2)
Mass remaining in lower layer storage	mg/m^2	83.9 (33.6)	116 (46.4)	75 (30.0)	115.9 (46.0)

* Metolachlor masses are expressed in mg per m^2 of field area. Numbers in brackets (100) represent percentages of applied metolachlor mass.



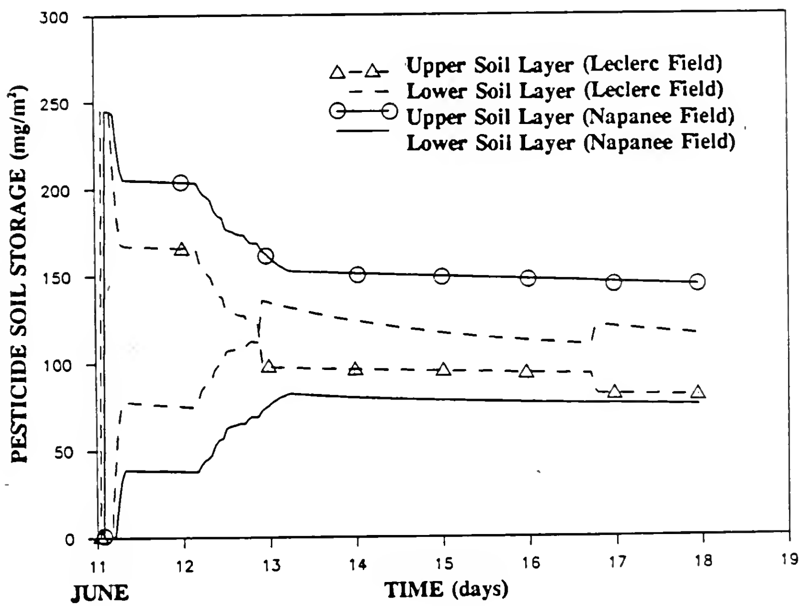


Figure 5.16 Comparison of pesticide stored in upper and lower soil layers for Napanee and Leclerc field soil characteristics

5.5.2 Tile Drain Spacing

The efficiency of the tile drainage system is dependent upon the effectiveness of the chosen drain density in removing excess water from the field soil. Soil properties and economic considerations are used to choose an appropriate tile drain spacing for a particular field. To investigate the effects of tile drain spacing on simulated pesticide fate, Napanee soil characteristics and three tile drain spacings (the actual spacing installed at the Napanee field, the spacing installed at the Leclerc field which is an appropriate spacing for a sandy loam soil and the spacing corresponding to the untiled case for the Napanee field) were employed. The May 19 and June 11, 1986 events were simulated using calibrated antecedent soil water contents and a standard application of 250 mg/m^2 of a chemical constituent with the properties specified for the pesticide metolachlor applied to the field surface just prior to the initiation of rainfall.

Table 5.8 lists the tile drain spacings employed and presents the pesticide fate simulation results. The water quantity simulation results were as presented in Table 5.2 for the two events investigated. Figure 5.17 illustrates the simulated pesticide transformation and runoff losses expressed as percentages of the applied mass. As shown in Figure 5.17, transformation losses were consistent for the two events and three tile spacings simulated at between eight and ten percent of the applied mass. Tile runoff losses, however, were reduced from approximately three percent of the applied mass for the actual Napanee field case (tile drain spacing of 12.2 m) to less than half of one percent for the untiled case (tile drain spacing of 85.4 m corresponding to two tile drains located at the field edges).

Figure 5.18 presents the corresponding pesticide mass storages in the upper and lower soil storage reservoirs for the two events simulated. Storage in the upper layer increased with increasing tile drain spacing reflecting the reduced soil permeability and subsequent reduced vertical constituent transport. Pesticide storage in the lower layer was reduced with increasing tile drain spacing as a result of increased constituent retention in the upper soil layer.

Table 5.8 Summary of metolachlor fate simulation results - effect of tile drain spacing

METOLACHLOR FATE RESULTS	UNIT	MAY 19, 1986 EVENT			JUNE 11, 1986 EVENT		
Tile Drain Spacing		**12.2 m**	**14.0 m**	**85.4 m**	**12.2 m**	**14.0 m**	**85.4 m**
Total mass applied to field	mg/m^2 •	250 (100)	250 (100)	250 (100)	250 (100)	250 (100)	250 (100)
Total mass lost in surface flow	mg/m^2	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total mass lost in tile flow	mg/m^2	8.2 (3.3)	6.7 (2.7)	0.5 (0.2)	6.9 (2.8)	6.0 (2.4)	0.4 (0.2)
Total mass lost to transformation processes	mg/m^2	20.8 (8.3)	20.9 (8.4)	21.2 (8.5)	23.9 (9.6)	23.0 (9.2)	23.2 (9.3)
Mass remaining in surface storage	mg/m^2	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Mass remaining in upper layer storage	mg/m^2	137 (54.8)	143 (57.2)	183 (73.2)	144 (57.6)	148 (59.2)	181 (72.4)
Mass remaining in lower layer storage	mg/m^2	83.9 (33.6)	79.4 (31.8)	45.7 (18.3)	75 (30.0)	73.0 (29.2)	45.1 (18.0)

• Metolachlor masses are expressed in mg per m^2 of field area. Numbers in brackets (100) represent percentages of applied metolachlor mass. Tile drain spacings of 12.2 m, 14.0 m and 85.4 m refer to the Napanee field, Leclerc field and undrained case spacings respectively.

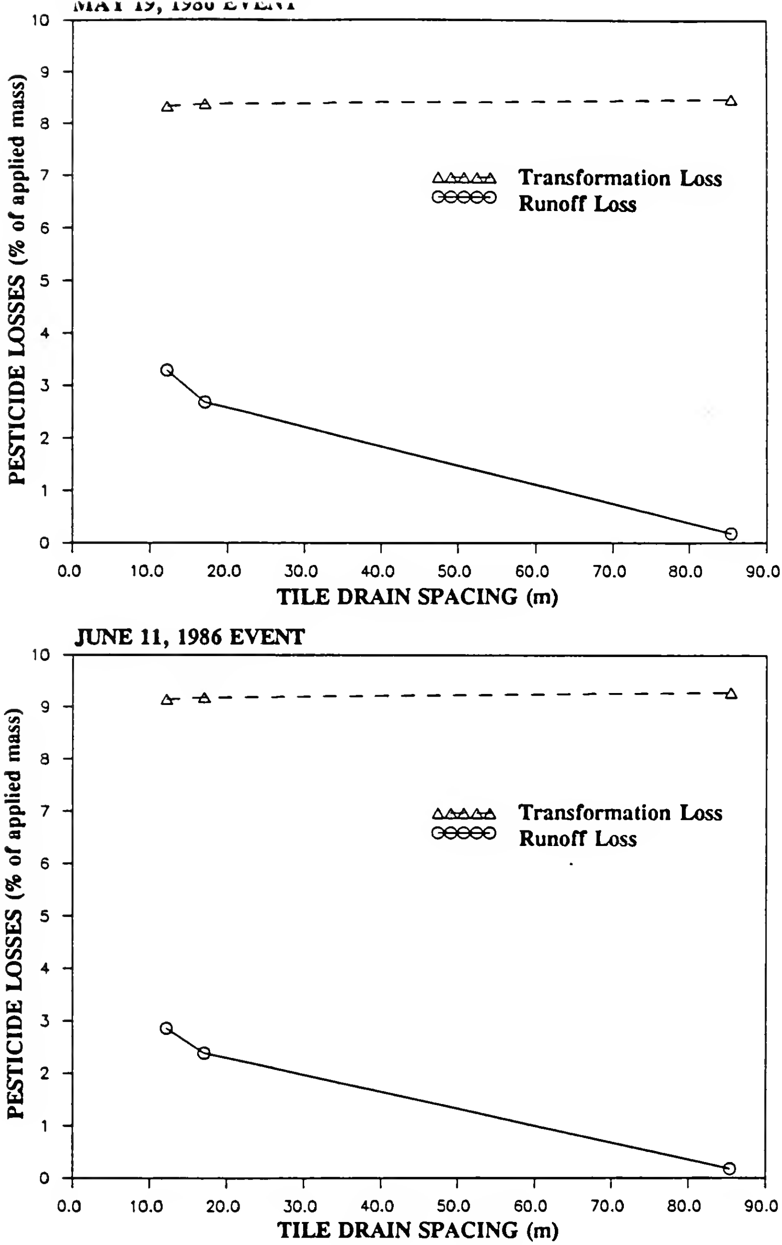


Figure 5.17 Effect of tile drain spacing on pesticide transformation and runoff losses

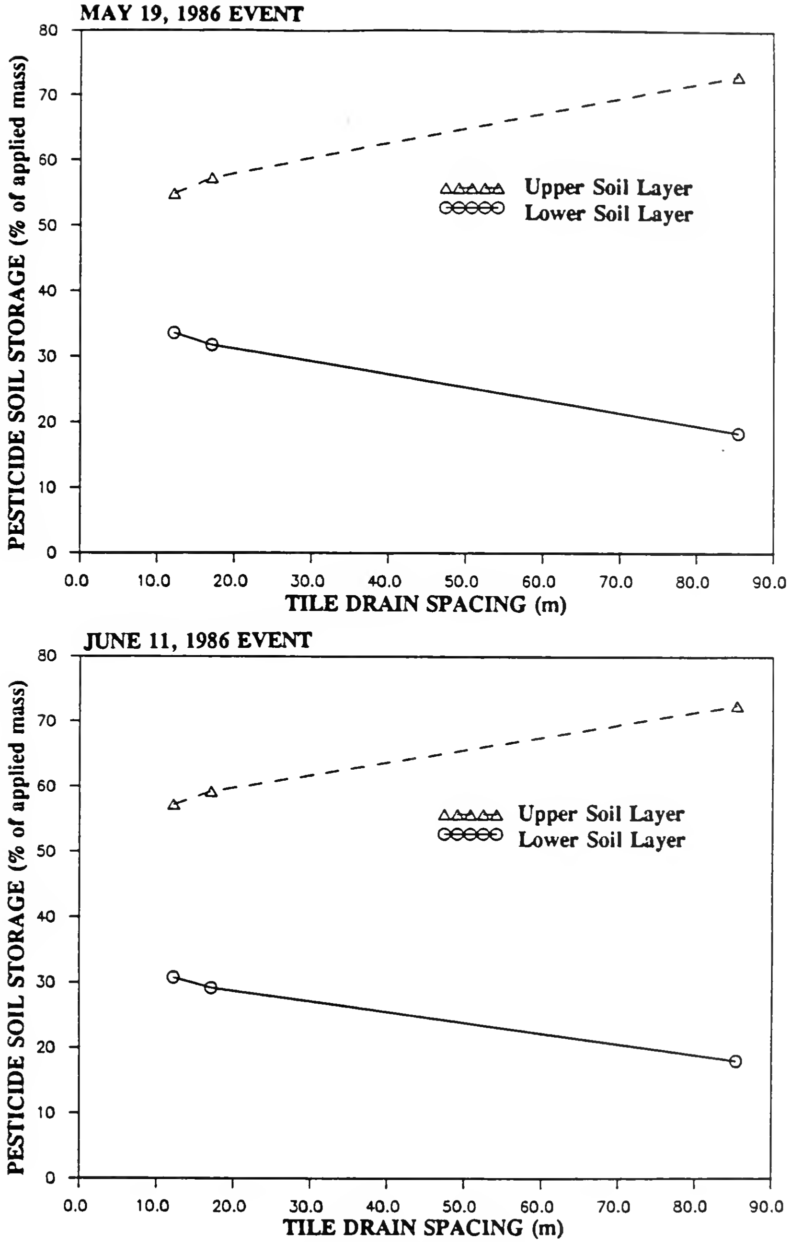


Figure 5.18 Effect of tile drain spacing on pesticide mass stored in upper and lower soil layers

6.0 IMPACTS OF TILE DRAINAGE ON WATER QUALITY

6.1 Impacts on Receiving Waters

6.1.1 Overview

The impacts of tile drainage on water quality can be considered at two levels:

- the outlet of a tile drain (field level), and
- the receiving water, a pond or a stream (basin level).

The impacts at the field level are field specific and contaminant specific and can be assessed using the methodology and model described in chapters 4 and 5. Of interest in this chapter are the impacts at the basin level. These inpacts cannot be inferred by a simple scaling up of the impact on a single field for three reasons. First, physiography, soil type, land use, contaminant type and loading are not constant over large areas. Second, physical and chemical processes in ditches, creeks and wetlands which connect fields have not been modelled and may, in some cases be significant (Examples are erosion, chemical decay and interaction). Third, the land use and drainage network will likely change if there is a major investment in tile drainage.

6.1.2 Detailed Analysis Using Small Basin Model

Given adequate data for algorithm development, calibration and verification, the best way to assess impacts on receiving waters is to employ a quality version of the "Small Basin Model" (Paine and Watt 1988) which was developed to model a system of tiled and untiled fields and ponds linked by channel elements. This approach was not attempted under this project because of the time and cost required for chemical data acquisition and testing.

6.1.3 Planning Analysis Using Field Model

In the absence of a calibrated chemical version of the "Small Basin Model", the field model can still be used as a planning in spite of the fact that various processes may be ignored.

Of primary interest to the water quality modeller concerned with a particular receiving

are estimates of flow and contaminant loading under specified tile-drainage intensity scenarios. Estimates of these can be obtained by using a simplified 'representative field' for each distinct soil type/land use/drainage state and contaminant type, scaling each up to account for the total area it represents, and transfer the resulting flows and loadings directly to the logical point of entry in the receiving water.

Outlined in the following sections are a qualitative assessment of major impacts on quality of receiving waters resulting from extensive tile drainage.

6.2 Peak and Low Flow Influence on Receiving Waters

Even if no contaminants were applied to tile-drained fields, the action of tile drainage will affect quality of receiving waters because of the changes in the flow regime. As shown in Paine and Watt (1988), both peak and low flows are affected by tile drainage. However, the reduction in low flow magnitudes is the predominant concern with respect to water quality. This reduction for a representative field and a particular climate can be determined using the model. For an average climate, low flows will be reduced to about one-half as a result of tile drainage. This reduction will effectively double any concentrations of contaminants in the receiving waters, and exacerbate high temperatures and low dissolved oxygen levels.

6.3 Quality of Tile Effluent

Under typical conditions, the major contaminant imput to receiving waters is via the tile effluent rather than surface runoff. For the actual events modelled (see chapter 5), which are typical large events following pesticide application, the tile effluent contained approximately three percent of the applied mass (There was no surface flow for either event). As indicated in chapter 5, the mass in the tile effluent is relatively insensitive to rainfall intensity and timing and pesticide characteristics. Typically, it ranges between two and four percent of applied mass. In incorporating these results into the planning exercise, the following points should be noted.

- Under a state of no tile drainage, the land may be used for a purpose that does not warrant the expenditure for pesticides. The change to tile drainage then results in a net

increase in pesticide loadings to receiving waters.

- Conversely, the use of pesticides may be justified under the undrained state. Thus, the change to tile drainage may not change land use and pesticide application. In this case, the three percent of applied pesticide in the tiled state may be much smaller than that carried by surface flow in the untiled state. Therefore, the change to tile drainage will result in a net decrease in pesticide loadings to receiving waters.

6.4 Quality of Surface Runoff

Under certain conditions as noted above, the major contaminant input to receiving waters is via surface runoff. The magnitude of this imput can be estimated from the actual events modelled (see chapter 5). There is a difference in surface runoff loading between untiled and tiled fields. Surface runoff loadings are significant only for surface application of contaminants (as opposed to incorporation) and for rainfalls with average intensity exceeding ultimate infiltration capacity (5 mm/h in the Napanee and Ottawa cases). For 6-h rainfall events with return periods ranging from 2-25 years, the surface runoff loading (% of mass applied) ranges from 13 to 47 for untiled fields and from 0 to 35 for tiled fields.

For any particular soil type, rainfall intensity and contaminant, the surface runoff loadings can be determined for both the tiled and untiled cases using the field model. Untiled scenarios are modelled by assuming the field side ditches act as "tiles" with a spacing equal to the width of the field (see Section 5.5.2).

7.0 CONCLUSIONS AND RECOMMENDATIONS

In response to rising concern about the potential for impairment of downstream water quality through the use of agricultural chemicals, in conjunction with current demands for increased agricultural productivity, a research project was undertaken to investigate the effect of subsurface tile drainage on the fate of agricultural chemicals. This project included the development and application of a physically based computer model, constructed on a framework of hydrologic processes and capable of simulation of chemical fate on a single agricultural field.

In the absence of a comprehensive data set, including measurements of chemical retention and runoff losses necessary for model calibration, the model was applied for a variety of scenarios using calibrated parameters for the water quantity components and values estimated from the literature for water quality parameters.

7.1 Conclusions

Specific conclusions arising from application of the model for a pesticide (metolachlor) applied to an experimental site located in southeastern Ontario (Napanee field) with field characteristics determined during previous investigations are given below.

1. For two rainfall events, slightly more than half of the applied pesticide was retained within the upper soil layer at the end of seven days. Pesticide losses due to transformation processes were larger than losses through tile drains and no pesticide mass was lost in surface runoff.

2. Pesticide losses to runoff were largest for high intensity rainfalls and pesticides applied to the field surface because of the high resultant losses to surface runoff. If the pesticide was incorporated within the upper soil layer, however, and thus protected from surface flow transport, simulated runoff losses were independent of rainfall intensity.

3. Pesticide fate depends on the time interval between pesticide application and rainfall. The longer the time interval, the more mass is lost to transformation processes. The time interval is especially critical for surface broadcast application because surface transformation losses are estimated to be an order to magnitude larger than losses due to soil transformation processes. In addition, evapotranspiration reduces the soil water content. The probability of occurrence of a rainfall event capable of generating surface flow was thus reduced for longer time intervals.

4. Pesticide fate was found to be dependent on chemical specific characteristics such as solubility in water. Pesticides with low solubilities were more slowly mobilized into the soil water and thus tile runoff losses were reduced for these chemicals. However, when low solubility pesticides were applied to the field by surface broadcast, pesticide which was not mobilized into the soil water early in the simulation period was available for transport by surface runoff generate by rainfall events occurring later in the simulation.

5. Higher tile flow volumes and correspondingly higher pesticide losses to tile runoff occur in higher permeability soils.

6. Larger values of tile spacing results in decreased tile flow and reduces vertical pesticide movement within the soil column.

Specific conclusions on the impacts of tile drainage on receiving waters are noted below.

7. The best method to assess impacts of tile drainage at a basin level is to employ a quality version of the small basin model but this approach requires extensive data for development and calibration.

8. A simplified assessment of basin scale impacts can be realized using an aggregate of individual representation field models.

9. Tile drainage impairs water quality during low flow periods because it reduces low flows to one-half the values occurring in the untiled state.

10. Pesticide inputs to receiving water from tile effluent range from two to four percent of the applied pesticide.

11. Pesticide inputs to receiving waters from surface runoff may vary from 13-47 percent for untiled areas and from 0-35 percent for tiled fields for rainfalls greater than the mean annual.

7.2 Recommendations

1. In light of the clear differences in contaminant loadings to receiving waters between surface application and incorporation methods, efforts should be made to encourage incorporation of the pesticide into the soil wherever possible.

2. In the conclusions, it has been shown that the model may be used to estimate flows and contaminant loadings to receiving waters under conditions of tile drainage. While this may be sufficient for a water quality modeller to assess the impact on the receiving stream or ponds, it does not improve water quality. What is required, therefore, is an evaluation of the effectiveness of potential remedial measures at the field and small basin model. The use of the model would be an integral part of this assessment for all likely combinations of topography, soil type, tile drainage, and contaminant. Also required would be a clear statement of receiving water quality targets for the various contaminants.

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